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ALTERNATIVE FORCE STRUCTURING  
STRATEGIES FOR MILITARY  
SATELLITE COMMUNICATION SYSTEMS

THESIS

William P. Murdock, Jr.  
Captain, USAF

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MILITARY SATELLITE COMMUNICATION SYSTEMS

THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Space Operations

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Approved for public release; distribution unlimited

## Preface

The purpose of this study was to consider alternative force structuring strategies for U.S. military satellite communication (MILSATCOM) systems. The Fleet Satellite Communication (FLTSATCOM) system was used as the baseline MILSATCOM system for comparison.

Low earth circular orbit constellations and a highly elliptical orbit (Molniya) constellation were examined. A methodology was developed to evaluate the performance of the alternative strategies. This methodology evaluated system effectiveness as well as system fabrication and launch cost. Although the detail of the alternative designs evaluated was at the system level, results showed the merits of the alternative force structuring strategies.

In performing the study and writing this thesis, I am indebted to the help provided by several people. First, I would like to thank my faculty advisor, Lt Col Parnell, for his advice and encouragement. Second, my readers, Maj Meer and Capt Tatman provided valuable insight and advice concerning this effort. I also wish to thank my sponsor, Maj Fitzgerald, USSPACECOM J4/6P, for his help. Finally, I wish to thank my wife Kay for her understanding and concern during those many hours I spent working on this study.

William P. Murdock, Jr.



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Abstract

The purpose of this study was to determine and examine alternative force structuring strategies for military satellite communication (MILSATCOM) systems. The study was undertaken due to the United States' reliance on relatively few, expensive satellites as critical communication links. Current anti-satellite weapons pose a definite threat to missions using this type of strategy. In response to this situation, proliferated MILSATCOM designs using low earth circular orbits and a highly elliptical (Molniya) orbit were defined and analyzed. The objective of this effort was to compare the proliferated alternative systems' performance and cost with a current MILSATCOM system. The Fleet Satellite Communication (FLTSATCOM) system was used as the baseline system for comparison.

For low earth circular orbit constellations, a constellation design parameter tradeoff analysis was accomplished. This tradeoff analysis along with a satellite transmit power model were used to identify specific constellations for further study. In addition, a highly elliptical constellation was also evaluated. This design was based on orbits used by the Soviet Union for communication satellites.

To assess system performance, alternative constellation earth coverage sensitivity to satellite losses was calculated. This measure of effectiveness was used to evaluate system performance in a hostile environment. The evaluation included global coverage sensitivity as well as the European theater and Mideast theater coverage sensitivities.

Overall, both alternative force structuring strategies provided superior earth coverage when subjected to satellite losses. This was especially evident in the European and Mideast theaters. The Molniya constellation was the best alternative when considering system performance, system cost, current MILSATCOM system compatibility and the technology required for system implementation.

# ALTERNATIVE FORCE STRUCTURING STRATEGIES FOR MILITARY SATELLITE COMMUNICATION SYSTEMS

## I. Introduction and Background

Both the United States and the Soviet Union accomplish very similar missions with their military satellites. These critical military missions include surveillance, reconnaissance, meteorology, geodetic surveys, navigation, and command, control and communication. However, the United States and the Soviet Union have developed distinctly different space force structuring strategies to support these military missions. The United States's strategy uses relatively few, very technically capable, long lifetime satellites. Often these satellites accomplish multiple missions (11:18-19). On the other hand, the Soviet Union's strategy uses numerous, less technically complex, shorter lifetime, single mission satellites (11:18-19). To support its space force structure, the Soviet Union launches about 100 satellites each year (1980 to 1985) (19). During the same period the U.S. launched about 25 satellites per year (19). With their greater launch capacity and more numerous satellites, the Soviet Union possesses a very flexible response capability during higher levels of conflict. In comparison, the current U.S. strategy becomes less responsive during higher levels of conflict. This strategy has

caused the U.S. to depend on limited launch resources and a few, high value satellites.

The U.S. depends on military satellite communications (MILSATCOM) systems to relay critical military command and control messages worldwide throughout the conflict spectrum (9:59). Experts estimate that over two-thirds of U.S. military long-haul communications travel through MILSATCOM links (3:40-51). One source estimates that "between 70 and 80 per cent of all U.S. long-haul military C<sup>3</sup> [command, control, and communications] is transmitted via satellite relays" (15:28). In the past, MILSATCOM systems were deployed with economics as the major consideration (11:18). Survivability and freedom of action throughout the conflict spectrum were given much less attention. As a result, the U.S. relies on a few, large, sophisticated, geostationary communication satellites (40). A weakness exists. If, during a conflict, an enemy denied the U.S. use of these critical communication links (by electronic warfare or anti-satellite weapons), U.S. military command and control would be severely degraded.

The 1982 National Space Policy addressed this situation. Concerning survivability and endurance, it says:

Survivability and endurance of space systems, including all system elements, will be pursued commensurate with the planned use in crisis and conflict, with the threat, and with the availability of other assets to perform the mission. Deficiencies will be identified and eliminated, and an aggressive, long-term program will be undertaken to provide more-assured survivability and endurance (15:111-112).

Additionally, the Department of Defense (DoD) recognizes the importance of space systems to U.S. military effectiveness.

The current DoD space policy states:

DoD will develop and maintain the capability to execute space missions regardless of failures of single elements of space support infrastructure. Specifically, tradeoffs between cost, lifetime, survivability, proliferation and related factors will be assessed during all phases to maximize mission capability. DoD will develop and maintain an assured mission capability through robust satellite control, assured access to space, and on-orbit sparing, proliferation or other means as appropriate (6:3).

These official statements on U.S. space policy justify the need for analysis of alternative MILSATCOM force structuring strategies. Additionally the United States Space Command has expressed much concern over future military satellite communication systems (40).

#### Problem Definition

During the initial deployment of artificial satellites, the U.S. was very much concerned with preserving space as a sanctuary. This philosophy saw space as a peaceful environment where systems would not be threatened. During those early years of space exploration, a peaceful environment existed and space systems operated in a virtual threat free (ie. man-made threats) environment. This situation combined with the cost of boosters served to justify larger, more complex satellites.

However, this situation does not exist today. Threats against satellites exist. These threats include co-orbital anti-satellite weapons (ASATs), direct ascent ASATs, space

mines, ground based and space based directed energy weapons, and nuclear warhead weapons. Communication systems such as the U.S. MILSATCOM will become increasingly vulnerable as the technology for these weapons is developed. Recently USAF Gen. John Piotrowski confirmed new satellite threats:

Twin ground-based lasers at Sary Shagan in the south-central Soviet Union are capable of killing U.S. satellites below 400 km. (248 mi.) in low Earth orbit and damaging satellites up to 1,200 km. (744 mi.) in space. The lasers also can cause inband damage to sensors and solar panels on satellites in geosynchronous orbit at 35,880 km (22,245 mi.) if transmitted over certain frequencies (27:27).

"Virtually all U.S. military communications and missile early warning satellites, as well as most signal intelligence satellites, are stationed in geosynchronous orbit" (27:27). Space cannot be considered a sanctuary. MILSATCOM systems must be designed to minimize the effects of an attack. Single node failure points must be eliminated through proper design and proliferation of critical components.

The current U.S. space force structuring strategy is lacking in several ways. It relies on relatively few, long-lived, expensive satellites to accomplish critical space missions. U.S. MILSATCOM systems accomplish one of these critical missions. Since these communication satellites are expensive, few in number, and often the only means that the U.S. has to communicate with remote areas, they become very high value targets. In addition to this undesirable situation, the U.S. is also unable to "surge" its space force

support capabilities to support a crisis. According to USAF Gen. John Piotrowski "if they [Soviet Union] attack our satellites [now], we can't put them back up fast enough" (27:27).

Problem statement. The current U.S. space force structuring strategy uses relatively few, long-lived, expensive satellites to accomplish critical missions. The U.S. relies heavily on military satellite communication (MILSATCOM) systems to link military command and control (C<sup>2</sup>) centers with field units. Soviet systems (e.g. ground based lasers) threaten these MILSATCOM systems. If these MILSATCOM systems were attacked, they may not be able to provide these critical military C<sup>2</sup> links. A requirement exists for a less vulnerable and fragile MILSATCOM force structure. Next generation MILSATCOM systems represent a timely opportunity to analyze alternative force structuring strategies. This analysis of alternative strategies must consider both system performance and system cost.

#### Scope

The purpose of this study is to analyze alternative MILSATCOM force structuring strategies. Specifically this study will consider MILSATCOM systems to replace the Fleet Satellite Communications (FLTSATCOM) system in its analysis of alternative force structuring strategies.

This analysis will develop system requirements for alternative force structuring strategies by considering

the FLTSATCOM system capabilities. A methodology will be developed to evaluate performance of alternative force structuring strategies against system requirements. This methodology will include evaluation of both military effectiveness as well as system fabrication and launch cost.

The alternative force structuring strategies analyzed will be based on technology available for FLTSATCOM. This assumption allows a direct comparison of the effects of force structure on system effectiveness and cost rather than one in which advanced technology is included. If an alternative force structuring strategy using an equivalent technology base is superior to the FLTSATCOM system, then the addition of advanced technology would make it even more superior.

The next chapter presents a literature review of satellite communication system design and cost analysis. This literature review will help develop the background necessary to perform the analysis described.



## II. Literature Review

### Scope

The research topic was limited to three areas. These three areas are as follows: alternative methods to structure a satellite communication system, space system and satellite cost models, and methods to assess the survivability of communication systems.

Data bases searched for relevant information included DTIC, DIALOG, STAR, the Engineering Index, Air University Library Index to Military Periodicals and the Applied Science and Technology Index.

### Method of Treatment and Organization

The discussion of the literature is arranged in a topical format. This section discusses each topic identified in the Scope section. These subsections are titled Alternatives, Commercial satellite cost models, and Survivability. Each subsection contains an informative discussion as well as comparison and contrast of the material presented within it.

### Discussion of Literature

This literature discussion will review alternative methods to structure a space communication system and then consider several cost models used to compare these alternative methods. Finally, a brief description of three

methods for assessing the survivability of a communication system will be presented.

Alternatives. Molette et al. (26) compares four alternatives to construct a satellite communication system. Their first alternative uses a "cluster of cooperative satellites" (26:772). This cluster of satellites included four active satellites with five spares, all stationed at geostationary orbit. The "cooperative" term used in describing this alternative refers to the intersatellite communications links needed for this system. Koelle (22) also considers a multiple satellite alternative in his paper. This alternative uses two satellites, each carrying a 650 kg communication payload (22:789).

Both studies analyze similar alternatives using large modular communication platforms stationed at geostationary orbit. Molette et al. (26) develop three large modular space platform alternatives. Two of these use an H-configuration platform. This platform is shaped like the letter "H". Solar panels form the legs. A service module with payload modules attached to it forms the cross member. One H-configuration alternative uses two payload modules, while the other H-configuration alternative uses four payload modules. These payload modules consist of the communication transponders and derive their power from the service module. The service module also takes care of orbit attitude and control functions. Molette et al. (26) also consider an H-configuration platform delivered to low earth orbit by the

shuttle and then boosted to geostationary orbit (26:772-773). Their other modular alternative is very similar to the one just described. This alternative is a Y-configuration modular platform consisting of solar panels, a service module, and four payload modules. The solar panels are attached perpendicular to the leg of the "Y." The service module is attached at the branch point of the "Y." Two payload modules are placed on each branch of the "Y" (26:772-773). The service and payload modules serve the same purpose as previously described.

Koelle (22) also compares two modular platform alternatives. One uses a service module with two payload modules while the other uses a service module with four payload modules (22:789). He does not offer a physical description of these platforms. Koelle also examined a single large spacecraft as one alternative. This alternative differed from the large modular platforms in that it was not a modular unit. Payloads could not be removed for servicing or replacement (22:789).

Vandenkerckhove (41) presents an interesting analysis of alternative space communication systems. He develops a relationship between the specific cost of the satellite per unit of payload power per year and the total satellite mass. By varying the number of payloads per satellite, he is able to make some interesting conclusions concerning satellite mass (41:765-770). This analysis differs from the previous ones in that no specific alternatives are defined. By

converting the measure of effectiveness to specific costs per unit of payload power per year, the author can study the sensitivity of several parameters to spacecraft size (mass) and lifetime. This allows him to make some rather general conclusions concerning alternative space communication systems (41:767-770).

Commercial satellite cost models. In assessing the relative effectiveness of a MILSATCOM system, economic cost is an important parameter. Several authors create specific cost models to generate costs for each alternative. Another author considers only the relative costs between each alternative. Vandenkerckhove (41), Molette (26), and Koelle (22) develop cost models to generate actual costs while Manger's cost model (25) uses a relative comparison. Manger's model normalized each alternative's cost to one specific alternative's cost.

In Vandenkerckhove's paper (41), a cost model for the total space segment is developed. The total space segment cost is based on the following formula (41:756):

$$C_{ss} = [ (1+u) ((NR/R) + (S_p)^{0.926}) + aS_L ] C_{SAT} + [ (1+a) (C_L + C_L') + (w + (w'/(1+\delta)) MTTF ) S_L ] S_L \quad (2.1)$$

where

$C_{ss}$  = cost of total space segment in accounting units(AU)

$u$  = overhead costs incurred by the procuring agency (AU)

$NR/R$  = nonrecurrent to recurrent cost ratio

$S_p$  = number of spacecraft procured

$S_L$  = number of launched spacecraft  
 $C_{SAT}$  = recurrent spacecraft (first unit) procurement cost (AU)  
 $C_L$  = unit launch costs, boost vehicle only (AU)  
 $C_L'$  = launch preparation costs, range and launch center costs (AU)  
 $w$  = variable part of yearly operations cost (AU)  
 $w'$  = fixed part of yearly operations cost (AU)  
 $a$  = risk of launch and early orbit failure  
 $\delta$  = number of spare satellites per active satellite  
 $MTTF$  = mean time to failure or average life of a satellite (years)

All costs shown are expressed in accounting units (AU). The author offers no explanation of this economic term. However, a subsequent paper defines one AU to be equal to \$1.38 (U.S.\$, 1983) (22:788). The recurrent spacecraft procurement cost,  $C_{SAT}$ , is the cost of the first unit procured. This cost is calculated by a formula dependent on spacecraft mass and the power requirements of the spacecraft (22:753). The author offers no derivation of this formula.

Koelle (22) presents a simpler cost model. His cost model is based on two parts. The first part determines first unit fabrication costs, while the second part calculates launch costs. The fabrication cost model is dependent on satellite mass. The author derived this model from actual data collected on various operating communication satellite systems (both military and commercial). The cost of each

satellite was plotted against the satellite mass. A trend was noted and the formula below was derived (22:787-788):

$$C = 11.1 (M)^{0.55} MY \quad (2.2)$$

where

C = cost of first unit fabrication in man years (MY)

M = mass of satellite (kg)

Koelle measures cost in man years (MY). He states, "the Man Year term remains constant and is not influenced by inflation or currency exchange rate fluctuation" (22:787). Koelle's launch cost model is also derived from actual data. Both expendable and semi-reusable launch vehicles are considered. The author plots the cost of the launch vehicle mass per unit mass of payload against the mass of the payload (satellite) (22:788). In the plot a trend is evident. However, the author does not reduce the launch cost relationship to a mathematical formula.

Manger (25) develops a parametric cost model for the space segment. The model considers the operational period for the system, the constellation size, the fixed useful lifetime of a spacecraft and the launch costs of the system. The cost model presented is as follows (25:796-797):

$$C = N [ 1 + f ((H/L) - 1) ] + [ 2.5 + \{ \delta, 0 \} + N + N ((H/L) - 1) (1 - \delta) ] [ BC_0 (L/2)^{\delta} ] \quad (2.3)$$

where

C = cost of total space segment (\$)

H = operational period for system (years)

N = constellation size (number of satellites)

$L$  = fixed useful lifetime of space segment (years)

$f$  = factor for extra launch costs incurred for on orbit repairs

$\{\delta, 0\}$  = if satellite is retrievable, the fraction,  $\delta$ , saved by retrieving; if not retrievable, then  $\delta=0$

$BC_s(L/2)^A$  = normalized recurrent costs per satellite

where

$B$  = extra cost factor for retrieval or on orbit repair designs

$C_s$  = recurring cost for a satellite with a design life of two years

$L$  = lifetime (years)

$A$  = cost fluctuation exponent to take into account varying design lifetimes

While this model takes into account the operational lifetime of a space system, it does not consider system operating costs or the risk involved with launch and retrievals (25:796-797).

The cost model presented in "Technical and Economical Comparison Between A Modular Geostationary Space Platform and A Cluster of Satellites" (26) normalizes the cost of each alternative to one specific alternative. This cost model includes lifetime, number of modules or satellites in orbit, number of ground spares, satellite dry mass in orbit, and the number and types of launch vehicles required (26:779). The authors do not derive the normalized cost values presented in the paper. One cannot tell whether these values are heuristic estimates or costs produced by some more rigorous means.

Survivability. Survivability is a critical parameter in assessing the overall effectiveness of a communication system. The following discussion presents three methods for determining survivability. In each method the communication system is represented by a network of nodes. The nodes represent the communication system components such as relay stations or satellites.

Chiang and Chiang (5) analyze a consecutive-k-out-of-n:F system. This description represents a system with n linearly arranged components such that the system fails when k consecutive components have failed. The model was originally developed to consider the survivability of communication links for deep space probes (5:65). A formula to calculate the expected number of relay stations needed to assure the communications link is presented. This formula is based on the reliability or survivability of each relay station, the total distance between the origin and destination and a system reliability function. The authors demonstrate how to analyze the tradeoff between cost and reliability or survivability (expressed as a probability) using their formula (5:66).

Heffes and Kumar (16) state the purpose of their analysis is "to construct a stochastic damage model, analyze it, and apply the results to the survivability analysis of some simple network topologies" (16:244). These topologies consisted of a star topology, a series connection, a parallel connection, and a communication link. The star topology



network consisted of a central hub with connections to outlying nodes. These nodes were linked to each other only through the hub. The series connection network considered a network where two nodes were connected in series. The parallel connection network considered the same network except the two nodes were connected in parallel. The communication link was a network of nodes connected in series. The distance between each node was held constant. Heffes and Kumar conclude in their paper that assuming independence between nodal damage events can lead to biased estimates of connection probability. Many previous methods assumed independence between nodes to simplify calculations. The end result of their analysis demonstrated that "assuming independence overestimates the probability of connectedness for the parallel configuration and significantly underestimates the connection probability for the series and communication link configurations" (16:239). The authors offer references (10), (30), and (42) as examples of methodologies where independence is assumed.

Benjamin (1) presents "a method to compute the probability of a through connection between any pair of nodes, A and B, in a network, whose elements are subject to known probabilities of destruction" (1:243). This algorithm is unique in that instead of considering all the various path combinations possible in a multiple node network to assess survivability, it uses surfaces spaced throughout the network to assess survivability. Each surface is comprised of

defined network nodes. The network nodes may lie in one and only one surface. At each surface probabilities for the through connecting nodes are calculated and used as the algorithm progresses sequentially through the surfaces from the source to the sink. The through connecting nodes have links to the source or sink. This algorithm greatly reduces the computational burden. For a 34 node network with 55 connections, the standard method of calculating the probability of a through connection by considering each and every path, required about 10.5 hours of central processor unit (CPU) time on a Cyber 740. Benjamin's algorithm solved the same problem with about 130 seconds of CPU time on the Cyber 740 (1:247).

### III. Alternative System Requirements and Measures of Effectiveness

Before starting an analysis of alternative force structuring strategies for UHF MILSATCOM systems, one must define the requirements served by the current UHF MILSATCOM communication system. Since the Fleet Satellite Communication (FLTSATCOM) system is the UHF MILSATCOM system serving as a baseline for this analysis, an overview of this system will be presented. Following this description of the FLTSATCOM system, consideration will be given to capabilities provided by this system. Finally, a determination of system requirements for alternative UHF MILSATCOM force structuring strategies will be made. Measures of effectiveness for determining how well these requirements are satisfied by alternative force structuring strategies will be discussed.

#### Fleet Satellite Communication System (FLTSATCOM)

The current FLTSATCOM constellation consists of six satellites in geosynchronous orbit. Five of these six satellites were fabricated under the original FLTSATCOM contract with TRW. Of the original five satellites, only four are operational on orbit. The fifth original satellite was damaged during the boost to orbit and provides essentially no operational capability. This left the original constellation with four operational satellites.

In June 1983 a new contract was signed with TRW to build three more FLTSATCOM satellites (31:366, 34:171). The fifth

operational satellite was built under this contract. Although all three new FLTSATCOM satellites were successfully completed under the contract, only one has joined the constellation. Of the two other satellites completed under this contract, one satellite was destroyed after a booster failure. The other satellite is in long term storage after its Atlas-Centaur booster was damaged beyond repair on the launch pad. Considering all of these effects, the current FLTSATCOM constellation consists of five operational satellites stationed at various points in geosynchronous orbit.

Purpose. FLTSATCOM provides users with ultra high frequency (UHF) communications. These users include all the services, but as one might suspect the U.S. Navy is responsible for the vehicle. In addition to its fleet support communications, the FLTSATCOM vehicle also carries an Air Force Satellite Communications (AFSATCOM) package. AFSATCOM provides communications for the Strategic Air Command (SAC) as well as supporting theater level operations. The purpose of the AFSATCOM system is as follows:

AFSATCOM provides reliable, enduring, worldwide command, control, and communications to designated Single Integrated Operational Plan (SIOP) nuclear capable users for: Emergency Action Message (EAM) dissemination, JCS-CINC internetting, force direction, and force report back. Additionally, AFSATCOM capacity is provided for a limited number of high priority non-SIOP users for operational missions, contingency/crisis operations, exercise support and technical/operator training (7:2-1).

Communication channels. FLTSATCOM provides several UHF channels. The Navy has 9 channels, each with a 25 kHz bandwidth. The AFSATCOM package consists of 12 channels, each with a 5 kHz bandwidth. All of these channels are accessed with a UHF uplink and broadcast by the satellite in the UHF band. The UHF band includes frequencies between 240 and 400 MHz (38:1).

Two other channels are in use on FLTSATCOM. First the Navy has a fleet broadcast channel. This channel serves to communicate messages where no response is needed. This channel is accessed by an super high frequency (SHF) signal. The satellite broadcasts the message in the UHF bandwidth. The second channel is the DOD wideband channel. This 500 kHz bandwidth channel is reserved for high priority DOD messages (38:1).

Specifications. Each FLTSATCOM vehicle weighs approximately 4153 pounds at liftoff. An Atlas-Centaur booster is used to place the vehicle in an elliptical transfer orbit. An integral apogee kick motor places the FLTSATCOM vehicle into its geosynchronous orbit (39:2-8).

The vehicle carries both a sun sensor and an earth sensor to keep its antennas pointing earthward (39:24-26). The UHF antenna consists of a 16 feet diameter parabolic mesh reflector (39:3). Other antennas include a UHF receive antenna, an S-band antenna and a super high frequency (SHF) antenna. These additional antennas are used to receive SHF uplink fleet broadcast signals, to receive UHF uplink signals

and receive and transmit S-band telemetry, tracking and command (T, T & C) signals (38:1).

Coverage. The FLTSATCOM constellation provides over 95 per cent coverage of the earth. The only regions not covered are the high latitude, polar areas. One satellite covers over 40 per cent of the earth's surface. This provides long distance communication links. With the use of ground stations, a message may travel around the globe.

Operational considerations. The Navy places specific channels on FLTSATCOM under the complete control of naval theater commanders (24). The Air Force apportions several AFSATCOM channels for full time SAC use. The bulk of AFSATCOM channels are scheduled through the Air Force Communications Command at Offutt Air Force Base. These channels are scheduled on as needed basis through user requests. Scheduling priorities have been established by the Joint Chiefs of Staff (21).

FLTSATCOM system capabilities. FLTSATCOM provides two capabilities to the various DOD user groups. First, it provides global coverage except for the high latitude polar regions. Second, it supports theater operations as well as providing the capability for global communication links through the use of ground stations.

The following list of desirable features for an alternative UHF MILSATCOM system was provided by USSPACECOM J4/6P (8).

1. Satellites must use a low earth orbit.

2. Satellites must use the current UHF satellite communication frequency band.

3. A method must exist to inhibit unauthorized users from accessing the system.

4. A network manager must be able to reallocate capacity to major user groups.

5. Payload operators must be able to electronically reapportion capacity to major user groups.

6. A network manager must be able to reallocate capacity to networks within his major user group.

7. Quick reaction repair and/or replenishment of the system to maintain a majority of its peacetime capability must be feasible both operationally and fiscally.

8. The alternative systems must geolocate UHF SATCOM jammers to within one square mile within 15 minutes.

#### Alternative System Requirements

Based on the capabilities provided by FLTSATCOM and the UHF MILSATCOM desirable features described by the USSPACECOM J4/6P, three major system requirements were established. First, the alternative system should provide global coverage at least to the extent that the current FLTSATCOM constellation does. Second, the major capability stressed in this analysis will be theater coverage. The alternative force structuring strategy should provide full theater coverage. This analysis will consider the European and the Mideast/Southwest Asian theaters. These theaters represent

primary strategic regions for the U.S. and its allies. Third, the alternative system design should minimize changes in the fielded UHF MILSATCOM user equipment.

Rationale. All areas of the earth are potential conflict regions. Remote areas may require communication links to satisfy operational activities in another region of the world. This dictates the requirement for global coverage.

Theater coverage may be an even more important than global coverage. Areas having high probability of crises and conflict need immediate and reliable communication links.

Finally, the large sunk costs in current UHF MILSATCOM user equipment dictate the requirement for alternative system compatibility with current user equipment.

#### Measures of Effectiveness (MOEs)

For global coverage, the measure of effectiveness will be the per cent of the earth's surface covered by at least one satellite. Coverage is defined as the per cent of the earth's surface continuously within the footprint of at least one satellite's antenna.

The same MOE will be used for theater coverage except that the per cent coverage figure will relate only to the area bound by the theater.

System performance of the alternative systems will be assessed by observing the sensitivity of earth surface coverage (both global and theater) to losses of satellites



from the system. System performance may be defined as the system's ability to complete its mission amidst a hostile environment, i.e. losing satellites.

Finally, the alternative systems' cost will be compared to current FLTSATCOM costs. These system costs will be based on the total cost for fabricating and launching the satellites in the system..

#### IV. Methodology

The methodology used to evaluate alternative UHF MILSATCOM force structuring strategies involved two distinct phases. The first phase identified feasible alternatives and then evaluated these constellation designs against the defined measures of effectiveness. Using these measures of effectiveness, a comparison between the alternatives and the current FLTSATCOM constellation was made. The second phase considered the fabrication and launch costs of the alternative constellation designs. This phase included a comparison between the alternatives and current FLTSATCOM costs.

##### Constellation Design

In a satellite communications system, many variables may affect the number of satellites needed in a constellation to provide global coverage. Given a constant number of satellites, there are an infinite number ways to arrange these satellites in a constellation. The major variables affecting constellation design include orbit altitude, orbit inclination, and the number of orbital planes in the constellation. For a fixed number of satellites, the number of orbital planes relates to the number satellites per plane.

Intuitively, to maintain maximum earth coverage with a constellation, one would want the orbits and satellites within these orbits to be symmetrically placed about the earth. However, this general statement concerning

constellation design does not relate the tradeoffs between orbit altitude, total number of satellites, number of satellites per plane, orbit inclination and earth coverage. For this reason a sensitivity study of these factors was performed.

Analysis tool. The sensitivity analysis concerning earth coverage and the parameters relating to constellation design was performed using a computer program that General Research Corporation developed for the Air Force Space Command. The tool is known as the Satellite Analysis Program (SAP) and is comprised of many utility programs. This analysis used the satellite coverage (SATCOV) program. SAP is written in Fortran and runs on a DEC Vax 11/780 (13).

SATCOV. SATCOV allows the analysis of constellation designs and earth coverage. Input parameters include each satellite's orbital parameters as well as its "sensor" field of view. In this case the sensor is a UHF parabolic reflector antenna. At each orbit altitude the beamwidth or field of view of the antenna was calculated to provide maximum earth coverage. Fig 4-1 shows how Eq (4.1) was derived (2:165):

$$BW = 2 * \arcsin[ R_E / (R_E + R_O) ] \quad (4.1)$$

where

BW = antenna beamwidth (angle measurement)

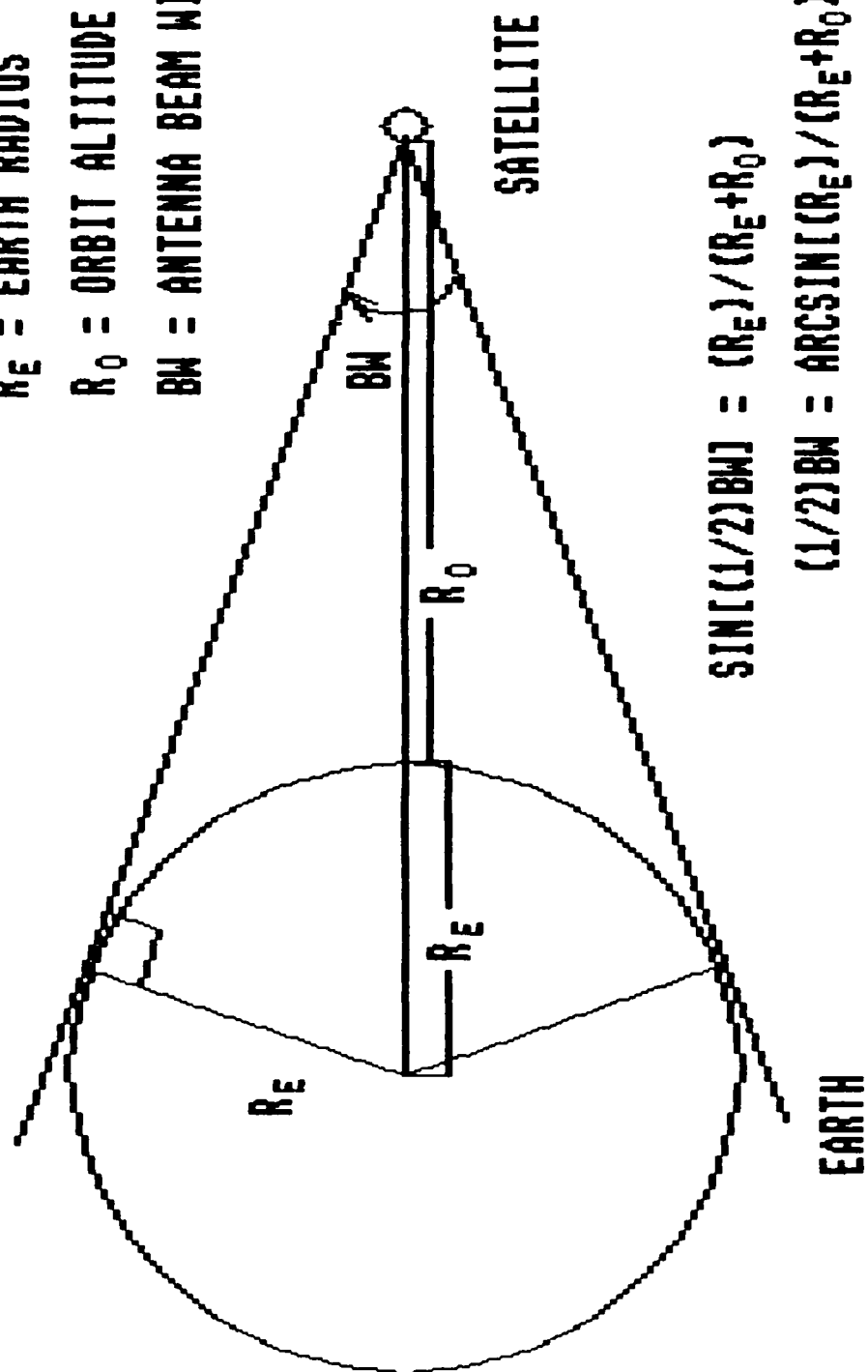
$R_E$  = radius of the earth

$R_O$  = orbit altitude

$R_E$  = EARTH RADIUS

$R_0$  = ORBIT ALTITUDE

BW = ANTENNA BEAM WIDTH



$$\sin[(1/2)BW] = (R_E) / (R_E + R_0)$$

$$(1/2)BW = \arcsin[(R_E) / (R_E + R_0)]$$

$$BW = (2) \arcsin[(R_E) / (R_E + R_0)]$$

Fig. 4-1 Calculation of Beam Width Angle to Maximize Earth Coverage

The sensitivity study varied the total number of satellites per constellation, the orbit altitude, the number of satellites per orbital plane and the orbit inclination. The output of SATCOV, per cent earth coverage, allowed tradeoffs between these factors and earth coverage to be evaluated.

The sensitivity study required multiple runs of SATCOV. Each run varied one of the parameters mentioned above while other parameters remained constant. Input orbital parameters included the east longitude of the ascending node at time zero, orbit inclination, the orbit perigee location relative to the east longitude of the ascending node, the apogee altitude, the perigee altitude and the orbit location of the satellite at time zero. The sensor parameters included maximum view angle, minimum view angle and depointing angle or the angle off the local vertical the sensor is pointing. Program control parameters included the desired observation times (start and end) and the step time interval to tell the program how many steps to make through the observation interval. The program allowed specification of particular ground points, areas consisting of grids of ground points or world coverage consisting of the earth's surface gridded into ground points (13).

The simulation propagated the satellites in their specified orbits from time zero to the specified starting observation time. Using a satellite's defined field of view to establish the satellite's footprint on the earth, the program

iterated through each ground point recording which ground points were in view of the satellite. This operation was performed for each satellite in the constellation. After finishing this task, the program propagates the satellites in their orbits by the specified step time interval. The process described above is then repeated. All of this continues until the observation time interval is completely stepped through by the specified step time interval (14:2.5-2.8).

At the discrete times in the observation time interval, various outputs are available. The most useful analysis output was the per cent of the earth's surface covered by at least one satellite at each discrete time. Coverage values for double, triple and more than triple satellite coverage were also given. Other output included maps detailing how many satellites covered each ground point at each discrete time.

This analysis used the single satellite coverage value. Since these values varied over the discrete times, a mean was calculated to obtain an overall single satellite coverage value for a specified constellation configuration. The results of this analysis are presented in Chapter V.

The results of the sensitivity study were used to select the constellation designs to carry forward in the analysis. This allowed definition of the orbit altitude and number of satellites per plane for specific alternative constellation design.

Required transmit power. Another key factor in constellation design is the required satellite transmit power. Power generation on a satellite is an important satellite design feature. For example, the FLTSATCOM electrical power and distribution subsystem weighs 721 pounds (39:8). Not taking into account the apogee kick motor, the satellite weighs 1871 pounds (39:8). The power system makes up 38 per cent of the spacecraft's weight (neglecting the apogee kick motor). Additionally the electrical power and distribution costs approximately 9.5 million dollars per satellite (36). This represents over 17 per cent of each satellite's total subsystem fabrication cost (36). Total subsystem fabrication cost does not include system engineering, test and evaluation, program management, and launch support costs.

The electrical power and distribution system is obviously a very critical subsystem. Many things may have an effect on the design of this subsystem. For this analysis, it is assumed that alternative design power generating capabilities will be equal to the current FLTSATCOM configuration (39:8). This assumption allows the development of a required transmit power model. This model will be used to evaluate alternative systems.

The consideration of required transmit power establishes basic feasibility of alternative constellation designs. The

required transmit power will limit the maximum altitude at which a constellation may be located. There are three factors affecting this consideration of required transmit power. First, as antenna beamwidth increases, the required beamwidth increases. Second, as altitude increases, the antenna beamwidth to provide maximum earth coverage decreases. Third, as altitude increases, free space loss increases requiring greater transmit power. Several opposing effects are at work as altitude increases. The following development of a required transmit power model captures the effect of altitude on free space loss and antenna beam width (set to the value which maximizes earth coverage at a given altitude). Eq (4.2) serves as a starting point (29:148):

$$(C/N_0) = (e.i.r.p./L_s)(G/T)(1/k) \quad (4.2)$$

where

$C/N_0$  = carrier to noise density ratio

e.i.r.p. = effective isotropic radiated power

$L_s$  = free space loss

$k$  = Boltzman's constant

$G/T$  = receiver antenna gain to system effective noise temperature ratio

Further definition of free space loss ( $L_s$ ) is required (29:148):

$$L_s = (4\pi R/r)^2 \quad (4.3)$$

where

$R$  = range distance

$r$  = wavelength of transmitted signal



The wavelength of the transmitted signal,  $\lambda$ , may be defined as shown in Eq (4.4) (32:758):

$$\lambda = (c/f) \quad (4.4)$$

where

$c$  = speed of light

$f$  = frequency of transmitted signal

Substituting Eq (4.4) into Eq (4.3) and completing the square, we obtain Eq (4.5):

$$L_e = (16\pi^2 R^2 f^2) / (c^2) \quad (4.5)$$

where all variables are as previously defined.

Eq (4.6) defines effective radiated power (e.i.r.p.) further (29:148):

$$\text{e.i.r.p.} = (P_T)(G_T) \quad (4.6)$$

where

$P_T$  = power input to antenna

$G_T$  = gain of transmitting antenna

The gain ( $G_T$ ) of a parabolic reflector antenna is defined in Eq (4.7) (12:72-73):

$$G_T = (4\pi/\lambda^2)(P_{AP})(A) \quad (4.7)$$

where

$G_T$  = gain of transmitting antenna

$\lambda$  = wavelength of transmitted signal

$P_{AP}$  = overall efficiency factor

$A$  = area of transmitting antenna

The area,  $A$ , for a parabolic reflector antenna is the area projected by the antenna surface onto a plane normal to the

direction of propagation. This area is described by Eq (4.8) (12:72-73):

$$A = \pi D^2/4 \quad (4.8)$$

where

$D$  = antenna diameter

Substituting Eq (4.4) for wavelength ( $\lambda$ ) and Eq (4.8) for antenna area,  $A$ , we obtain Eq (4.9) (35:101):

$$G_T = [(\pi^2 D^2 f^2)/(c^2)](P_{AP}) \quad (4.9)$$

where

$G_T$  = gain of parabolic transmitting antenna

$D$  = diameter of parabolic transmitting antenna

$f$  = frequency of transmitted signal

$c$  = speed of light

$P_{AP}$  = overall efficiency factor

Usually,  $P_{AP}$  for parabolic reflector antennas is about 0.55 (Pratt: 81). The carrier to noise density ratio ( $C/N_o$ ) may be defined as shown in Eq (4.10) (29:223):

$$(C/N_o) = B_R(E_B/N_o) \quad (4.10)$$

where

$B_R$  = bit rate

$(E_B/N_o)$  = bit energy to noise density ratio

Substituting Eq (4.10) in Eq (4.2), Eq (4.11) is obtained:

$$B_R(E_B/N_o) = (e.i.r.p./L_e)(G/T)(1/k) \quad (4.11)$$

where all variables are as previously defined.

Substituting Eq (4.5) for  $L_e$ , Eq (4.6) for e.i.r.p. and Eq (4.9) for the antenna gain,  $G_r$ , term in Eq (4.6), Eq (4.12) is obtained:

$$B_R(E_B/N_0) = P_T[(\pi^2 D^2 f^2)/(c^2)](P_{AEP}) * [(c^2)/(16\pi^2 R^2 f^2)](G/T)(1/k) \quad (4.12)$$

where all variables are as previously defined.

Cancelling terms and solving for required transmit power,  $P_T$ , we obtain Eq (4.13):

$$P_T = B_R(16R^2/D^2)(1/P_{AEP})\{1/[(G/T)/(E_B/N_0)]\}(k) \quad (4.13)$$

where

$P_T$  = required transmit power

$B_R$  = bit rate

$R$  = slant range (transmitter to receiver)

$D$  = antenna diameter

$P_{AEP}$  = overall efficiency factor

$k$  = Boltzman's constant

$(G/T)/(E_B/N_0)$  = combined receiver/transmitter performance parameter

This model for required transmit power is very optimistic. First, it does not include attenuation due to atmospheric loss. Second, no provisions are allowed for an anti-jam capability. These limitations will be handled as follows. Since the alternative designs have the same RF and prime power generating capabilities and essentially the same configuration as the FLTSATCOM satellites, a required transmit power level using FLTSATCOM specifications will be

calculated using Eq (4.13). This value will be compared to the actual power transmitted by FLTSATCOM transmitters. The calculated value will be much less than the actual power transmitted. The difference between the two will be attributed to attenuation losses and anti-jam capability not taken into account in Eq (4.13). Therefore, the calculated value from Eq (4.13) for FLTSATCOM will be used as the limiting power level for the alternative designs.

For a parabolic antenna, beamwidth (BW) may be approximated by the following relationship (37:159-160):

$$BW = r/D \quad (4.14)$$

where

BW = antenna beamwidth (radians)

$r$  = wavelength of transmitted signal

D = antenna diameter

Solving for D, antenna diameter and substituting Eq (4.4) for  $r$ , wavelength of transmitted signal, we obtain Eq (4.15):

$$D = (c)/[(f)(BW)] \quad (4.15)$$

where all variables are as previously defined.

Eq (4.15) expresses the antenna diameter in terms of transmitted signal frequency and antenna beamwidth. It is assumed that antenna beamwidth is set for maximum coverage at a given orbit altitude. Fig. 4-1 explained the derivation of

this relationship. Eq (4.1) is substituted for antenna beamwidth (BW) and Eq (4.16) is obtained:

$$D = (c) / \{2f[\arcsin\{(R_E)/(R_E + R_O)\}]\} \quad (4.16)$$

where

D = parabolic antenna diameter

c = speed of light

f = frequency of transmitted signal

R<sub>E</sub> = radius of the earth

R<sub>O</sub> = orbit altitude

The slant range, R, from Eq (4.13) is calculated as follows. We are interested in the maximum required transmit power. This occurs at the maximum slant range. Fig. 4-2 pictorially explains Eq (4.17):

$$R = [(R_E + R_O)^2 - (R_E)^2]^{1/2} \quad (4.17)$$

where

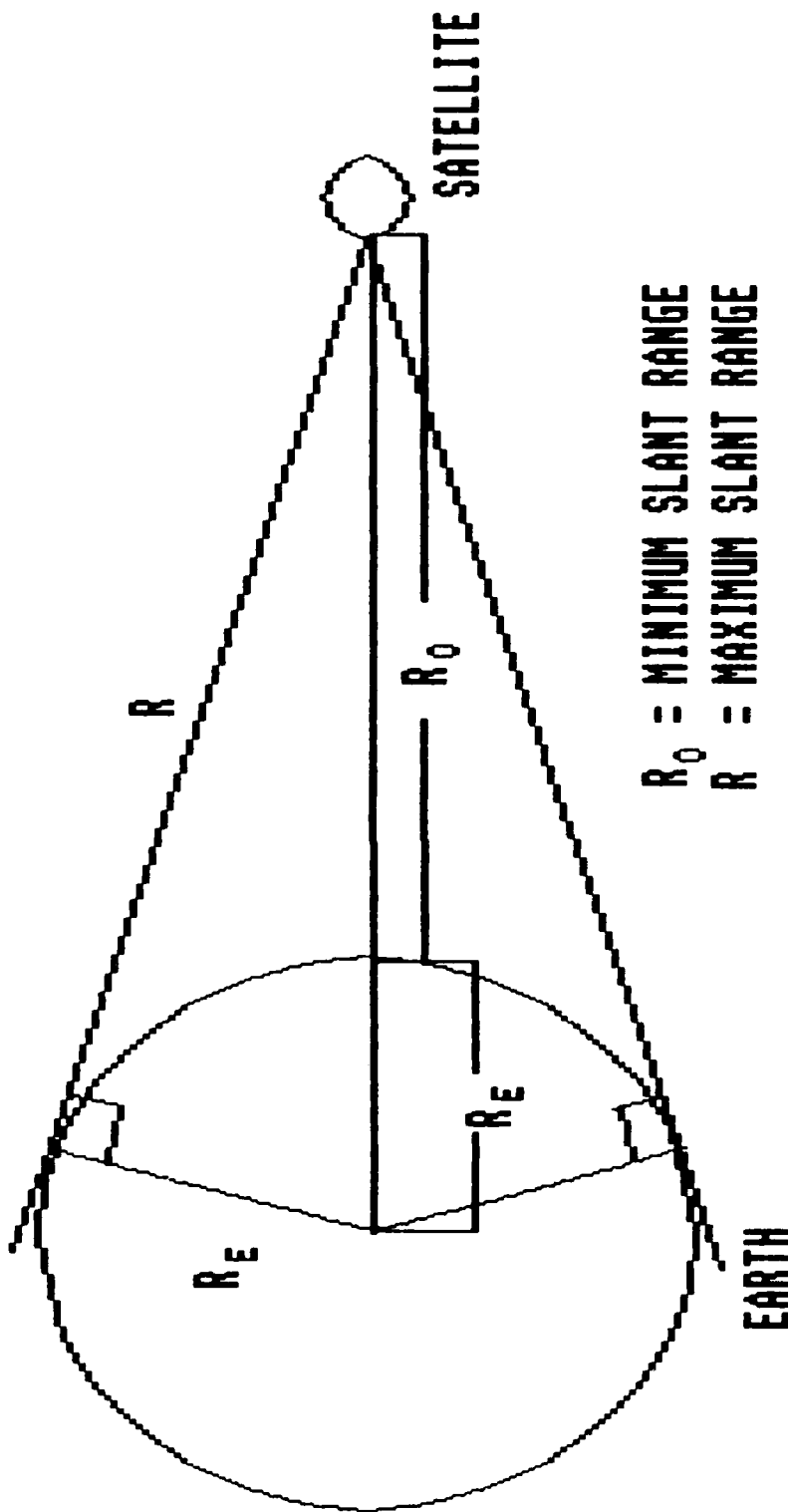
R = maximum slant range

R<sub>E</sub> = radius of the earth

R<sub>O</sub> = orbit altitude

From Fig. 4-2 slant range varies from a minimum equal to the orbit altitude to a maximum equal to the distance R, described by Eq (4.17).

A Fortran program was written to evaluate the required transmit power at various altitudes. Note that these transmit power levels assume that antenna beamwidth maximizes earth coverage at a given altitude. Required transmit power levels were calculated both for minimum and maximum slant range. Power levels were expressed in both watts and dBm.



$R_0$  = MINIMUM SLANT RANGE

$R$  = MAXIMUM SLANT RANGE

$$R^2 + R_E^2 = (R_E + R_0)^2$$

$$R^2 = (R_E + R_0)^2 - R_E^2$$

$$R = [(R_E + R_0)^2 - R_E^2]^{(1/2)}$$

Fig. 4-2 Maximum Slant Range

The following equation expresses how dBm power levels were calculated (33:120-121):

$$\text{dBm} = 10 \log_{10} [(P_T)/(0.001)] \quad (4.18)$$

where

dBm = decibel measurement relating power to 1 mW level

$P_T$  = required transmit power in watts

Chapter V will describe the specific values used in calculating required transmit power levels.

Selecting alternative constellation designs. Through the use of the earth coverage sensitivity study and the required transmit power level, alternative constellation designs may be selected for further analysis.

The sensitivity study will show the relative tradeoffs between the constellation design parameters. These parameters include the number of satellites, the number of satellites per orbital plane, the orbit inclinations and the orbit altitude. The sensitivity analysis results will allow points of diminishing returns to be identified. In the specific analysis, constellation design parameters will be compared to orbit altitude. For example, constellation satellite quantity, number of satellites per orbital plane and orbit inclination will be held constant while altitude is allowed to vary. These results will be plotted allowing easier interpretation.

After considering the results of the sensitivity analysis to find points of diminishing return, the required

transmit power model will be used to find orbit altitudes that are feasible.

System performance. This step in the analysis evaluates the performance of the alternative constellation designs selected for further study. Each alternative constellation design will be evaluated against earth coverage sensitivity to losses of satellites from the constellation.

The SAP SATCOV program will be used to perform the analysis. For each constellation design, computer runs will be made. These runs will remove satellites from the constellation and record the earth coverage provided each time a satellite is removed. Coverage values were obtained by averaging values as described earlier. Both global and theater coverage levels will be evaluated. FLTSATCOM performance will also be evaluated to provide a point of comparison.

#### Cost Analysis.

The cost analysis methodology entails the use of FLTSATCOM costs. As stated earlier, all alternative constellation satellite designs will be based on the current FLTSATCOM satellite design.

Since the evaluation of lower earth orbit constellations will be performed, the unit costs generated for alternative constellations will not include the cost for the apogee kick motor (AKM). The AKM does not represent a large percentage of the total cost of the satellite. About 6.5 per cent of



the total subsystem fabrication cost is attributed to the AKM (36). However, the AKM represents almost fifty per cent of the satellite's liftoff weight (39:8). By eliminating the AKM, the liftoff weight is reduced from 4153 pounds to approximately 2100 pounds (39:8). All launch costs for the alternative designs will be based on this lift-off weight.

Learning curves. All cost analysis accomplished will show the effects of learning. Learning may be defined as the reduction in unit costs as more and more units are produced. A cost model representing total system launch and fabrication cost will be developed. Learning will be applied to the satellite fabrication cost component of the model.

The total system fabrication cost is developed in the following discussion (4):

$$U_x = KX^B \quad (4.19)$$

where

$U_x$  = average unit fabrication cost at  $X^{th}$  unit

$K$  = first unit fabrication cost

$X$  = number of units produced

$B$  = exponent relating to the learning rate

$B$ , the exponent relating to the learning rate is defined as follows (4):

$$B = \ln(S)/\ln 2 \quad (4.20)$$

where

$S$  = the learning rate

As  $S$ , the learning rate, decreases the  $B$  value decreases. If all other values remain constant in Eq (4.19), then the

$U_x$ , the average unit fabrication cost at the  $X^{th}$  unit, decreases. For example, at a learning rate of  $S=1$ , the exponent  $B$  goes to zero and the  $U_x$ , average fabrication cost per unit at the  $X^{th}$  unit, remains constant at the first unit fabrication cost,  $K$ . However, at a learning rate of less than one ( $S < 1$ ), the exponent  $B$  is less than one and the  $U_x$ , the average fabrication cost per unit at the  $X^{th}$  unit, decreases.

By defining  $B$  in Eq (4.20) as the natural log of the learning rate ( $S$ ) divided by the natural log of two allows the  $U_x$ , the average fabrication cost per unit at the  $X^{th}$  unit to decrease as the learning rate,  $S$ , remains constant (and is less than one) and  $X$ , the number of units produced increases. This decrease allows the average unit fabrication cost at unit  $Y$  to be  $S$  (the learning rate) times the average unit cost at unit  $(1/2) Y$ . For example at a learning rate of  $S=0.95$ , the average unit fabrication cost at unit 10 will equal to 0.95 the average unit fabrication cost at unit 5.

Eq (4.19) may be manipulated to obtain the total system fabrication cost for  $X$  units (4):

$$F_x = XU_x \quad (4.21)$$

where

$F_x$  = total system fabrication cost for  $X$  units

$X$  = total number of units in system

$U_x$  = average unit fabrication cost at  $X^{th}$  unit

Substituting Eq (4.19) for  $U_x$ , Eq (4.22) is obtained (4):

$$F_x = XKX^B = KX^{(B+1)} \quad (4.22)$$

where

$F_x$  = total system fabrication cost

$K$  = first unit fabrication cost

$X$  = number of units in system

$B = \ln(S)/\ln(2)$

Eq (4.22) represents the total system fabrication cost.

Now, the system launch cost portion of the the total system launch and fabrication cost model will be developed. Launch cost for a single satellite may be represented as follows:

$$L_x = WQ \quad (4.23)$$

where

$L_x$  = unit launch cost (\$)

$W$  = unit weight (lbs)

$Q$  = average launch cost per unit weight (\$/lb)

To obtain the total system launch cost, we can multiply Eq (4.23) by  $X$ , the number of units to be launched. Eq (4.24) is obtained:

$$TL_x = L_x X = WQX \quad (4.24)$$

where

$TL_x$  = total system launch cost

$X$  = number of units to be launched (i.e. number of satellites in system)

All other variables are as previously defined.

To obtain the total system fabrication and launch cost, we add Eqs (4.22) and (4.24):

$$T_x = KX^{(B+1)} + WQX \quad (4.25)$$

where

$T_x$  = total system launch and fabrication cost

All other variables are as previously defined. Eq (4.25) represents the cost model to be used to calculate system fabrication and launch cost.

Fabrication costs. Fabrication costs for alternative designs will be based on those obtained for FLTSATCOM. This analysis assumes that all alternative designs are based on current FLTSATCOM costs. Chapter V offers a breakdown of these costs.

Launch costs. Launch costs will be handled parametrically. Plots will be developed showing system cost sensitivity to launch cost. Launch costs will be expressed as a dollar per pound of payload cost. The launch cost per unit will equal the unit weight times the launch cost per pound (\$/lb). This figure will be used to calculate the system launch cost. It will then be added to obtain the total system fabrication and launch cost.

In Chapter V, the methodology presented above will be used to analyze several specific alternative FLTSATCOM constellation designs.

## V. Results

Using the methodology presented in Chapter 4, this chapter presents the results of the orbital parameter tradeoff study, the required transmit power calculations, and the sensitivity of earth coverage to satellite losses. Earth coverage sensitivity for global as well as the Mideast theater and the European theater is presented.

The analysis considered lower earth orbit constellations as replacement FLTSATCOM systems. Low earth constellations were identified as a top priority for alternative systems by the USSPACECOM (8). The analysis entailed the following four steps:

1. A tradeoff analysis of constellation design parameters and their effects on global coverage was accomplished. These constellation design parameters were the total number of satellites in the constellation, the number of orbital planes, orbital plane inclination, and orbit altitude. Global coverage was defined as the per cent of the earth's surface constantly in view of at least one satellite.

2. Feasible altitudes to transmit from were established using the required transmit model developed in Chapter IV. Since all alternative satellites were considered to be identical in design to the FLTSATCOM spacecraft, it was assumed that their transmit power would be limited to that available from the current FLTSATCOM design.

3. By combining the results of constellation design tradeoff study and the required transmit power calculations,

two specific constellation designs were selected for sensitivity study. This sensitivity study showed how earth surface coverage changes as satellites are lost from a constellation. The analysis included the FLTSATCOM configuration for comparison purposes. This portion of the study considered three regions: global, the Mideast theater and the European theater.

4. A cost analysis of the alternative designs is presented. FLTSATCOM system costs are provided for comparison.

#### Constellation Design Parameters Tradeoff Study

The objective of this phase was to analyze the tradeoffs between lower earth orbit constellation design parameters and global coverage.

Constellation design parameter values. In designing the lower earth orbit constellations, the following assumptions were made:

1. All orbits within a constellation were circular.
2. All orbits within a specific constellation had the same altitude.
3. Ascending nodes of the orbital planes within a constellation were evenly spaced about the equator.
4. Satellites within an orbital plane were evenly distributed about the plane. For example, with three satellites per orbital plane, the satellites were placed at

0, 120 and 240 degrees true anomaly at the simulation start time.

5. The satellite antenna beamwidth angle was set to maximize earth coverage at each specific altitude examined.

Table 5-1 summarizes the alternatives evaluated in the tradeoff study. The altitude range was discretized to 10 points for all constellation designs. The value ranges shown in Table 5-1 identified 270 separate constellation configurations. Each configuration required a SAP/SATCOV computer run for evaluation.

Relative phasing. Relative phasing of satellites between orbital planes was accomplished for cases using two satellites per plane. This was done by shifting the placement of satellites within each orbital plane. Consider the twelve satellite constellation with two satellites per plane. This twelve satellite configuration allows a total of six orbital planes, each with two satellites per plane. First, each orbital plane's ascending node was placed at 60 degree increments about the equator to achieve even spacing between the orbital planes. Next the relative phasing of the satellites was considered. Picking any orbital plane as a starting point, the satellites in this plane were placed at 0 and 180 degrees true anomaly. The next plane contained satellites at 60 and 240 degrees true anomaly. This process of adding 60 degrees to each satellite's initial position was continued until all six orbital planes were filled.

**Table 5-1 Alternative Constellation Design Parameters**

<b>CONSTELLATION SIZE NUMBER OF SATELLITES</b>	<b>ALTITUDES (KM)</b>	<b>ORBIT INCLINATIONS (DEGREES)</b>	<b>NUMBER OF SATELLITES PER ORBITAL PLANE</b>
<b>12</b>	<b>500 TO 5000</b>	<b>30</b>	<b>2</b>
		<b>45</b>	<b>3</b>
		<b>60</b>	<b>6</b>
<b>18</b>	<b>500 TO 5000</b>	<b>30</b>	<b>2</b>
		<b>45</b>	<b>3</b>
		<b>60</b>	<b>6</b>
<b>24</b>	<b>500 TO 5000</b>	<b>30</b>	<b>2</b>
		<b>45</b>	<b>3</b>
		<b>60</b>	<b>6</b>

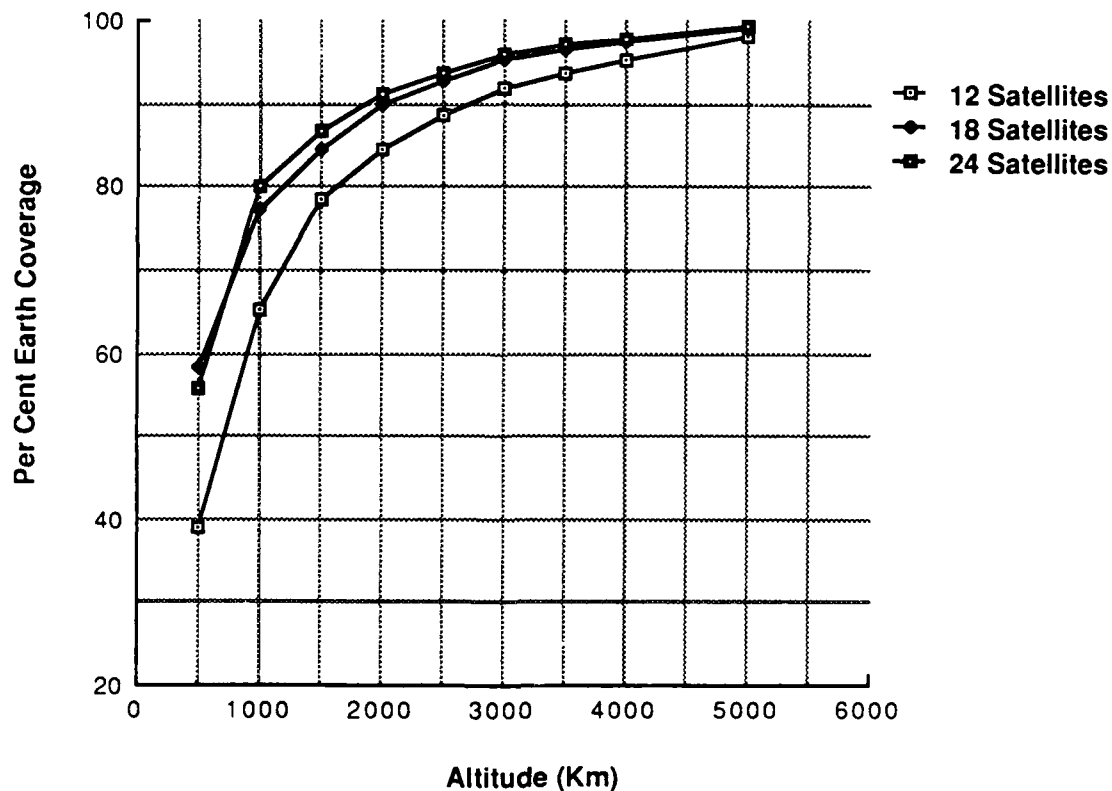


For the constellations having different numbers of orbital planes (than the case just described), the positioning of the orbital planes' ascending nodes was determined by taking the number of orbital planes and dividing by 360 degrees. This value represented the number of degrees between the orbital planes' ascending nodes. For relative phasing, this value also represented the number of degrees to offset the satellites' true anomalies in each succeeding orbital plane.

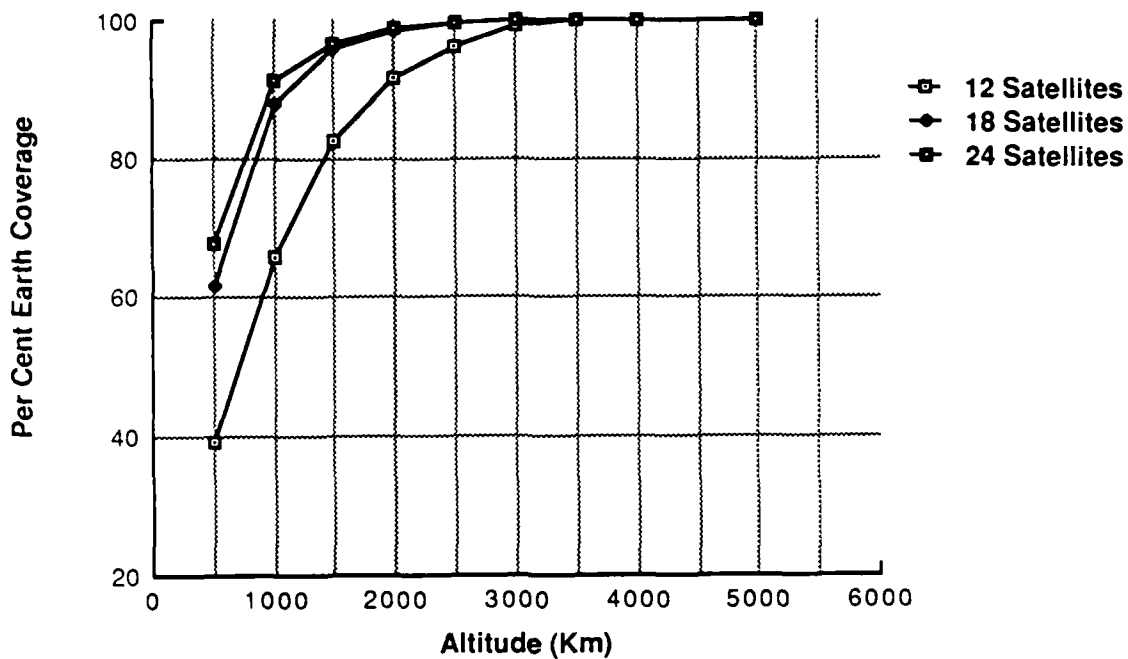
For the cases involving three and six satellites per orbital plane, relative phasing was not considered. Satellites were placed evenly in each orbital plane. All orbital planes had satellites starting at the same true anomalies. Results obtained from this analysis showed that as the number of orbital planes decreased the effects of relative phasing on global coverage decreased. Some improvement in global coverage for the three satellites per plane cases would be expected with relative phasing. Even less improvement would be expected for the six satellites per orbital plane cases.

Mechanics of tradeoff study analysis. Since this study involved approximately 270 separate computer runs, a standard methodology was applied. This involved setting up SAP/SATCOV data files in which the total number of satellites, orbit inclination, and number of satellites per plane all remained fixed while altitude varied. For example, a data file for the 12 satellite constellation with 30 degree

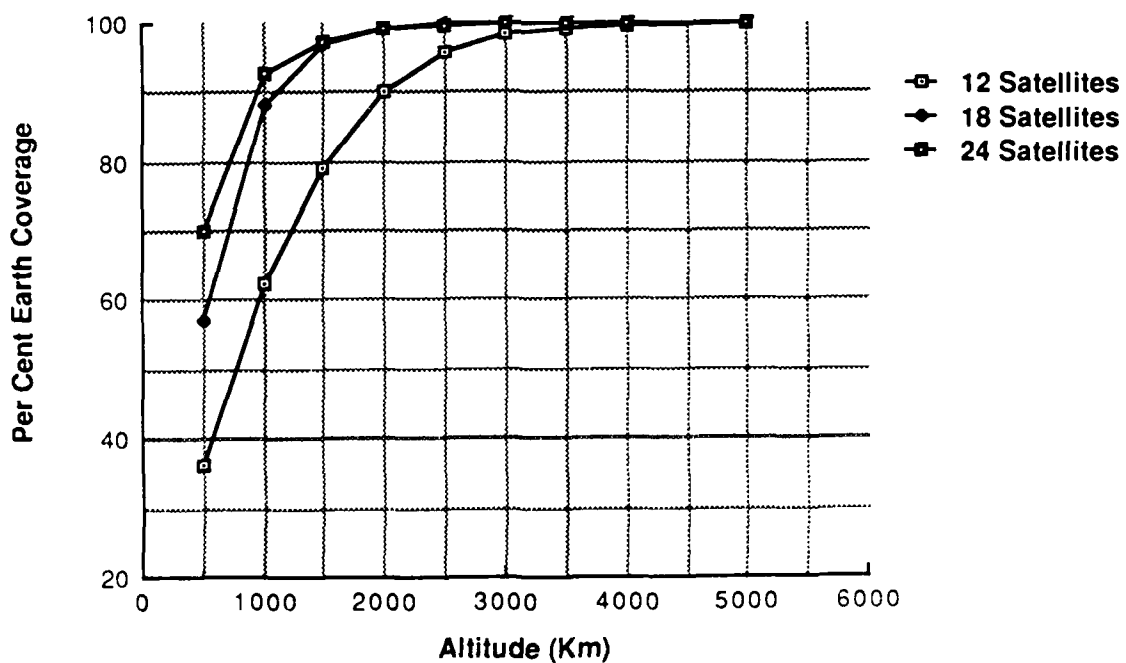
orbital plane inclinations and two satellites per plane (six planes) at an altitude of 500 km was created. Then the altitude specification was modified so a total of 10 or 12 data files were created where only altitude varied. Altitude ranged from 500 km to 5000 km. All other design parameters remained fixed. This technique was used for all alternative constellation designs shown in Table 5-1. Results of this analysis are presented in Figures 5-1 through 5-9.



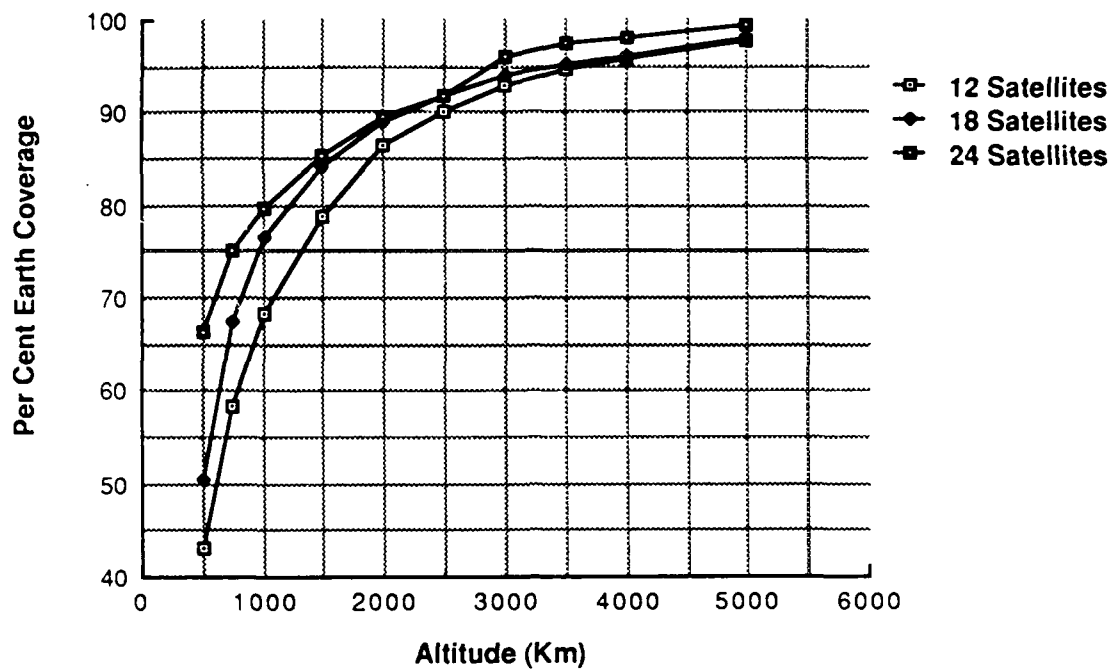
**Fig. 5-1 LEO Global Coverage**  
**For  $i=30$ , 2 Satellites Per Plane**



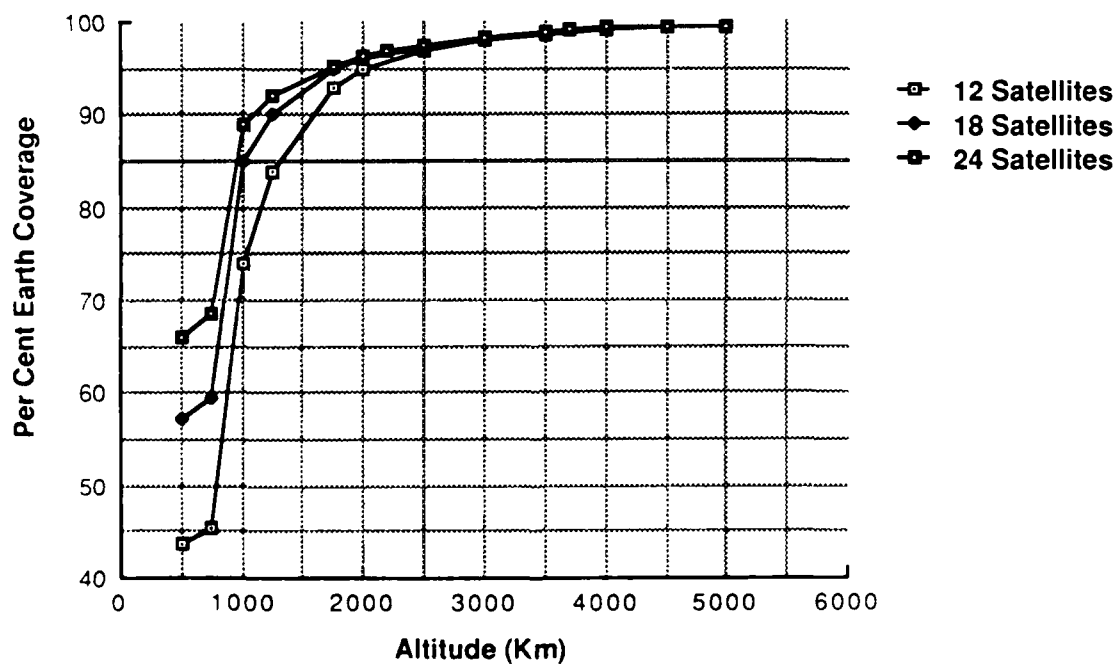
**Fig. 5-2 LEO Global Coverage**  
For  $i=45$ , 2 Satellites Per Plane



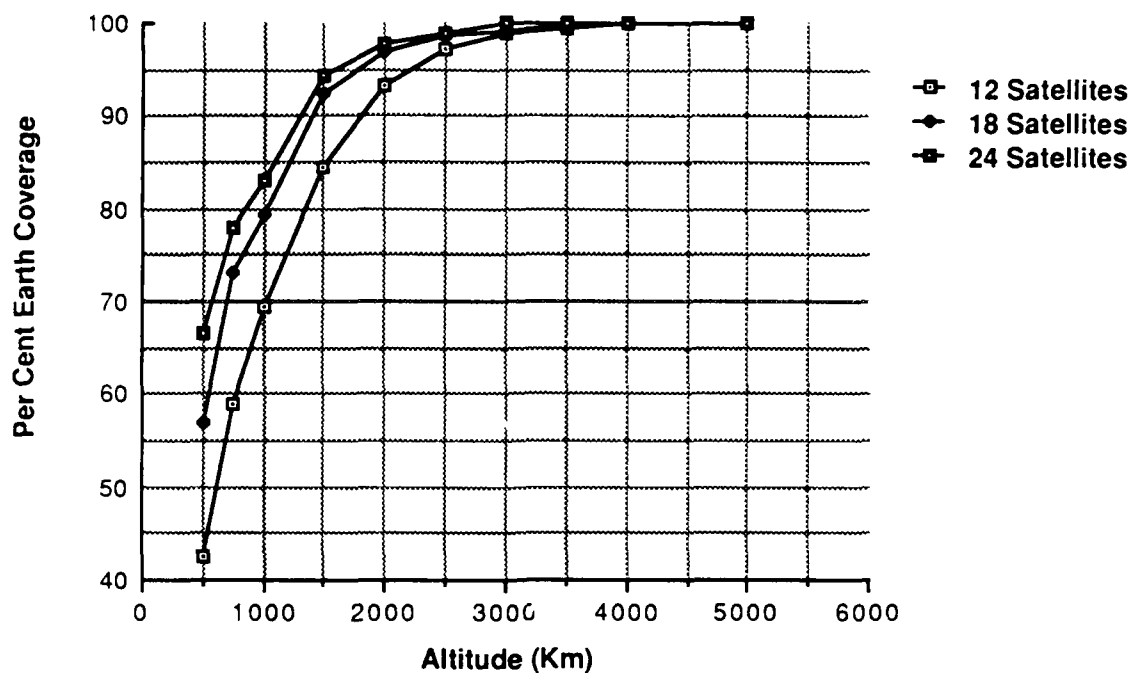
**Fig. 5-3 LEO Global Coverage**  
For  $i=60$ , 2 Satellites Per Plane



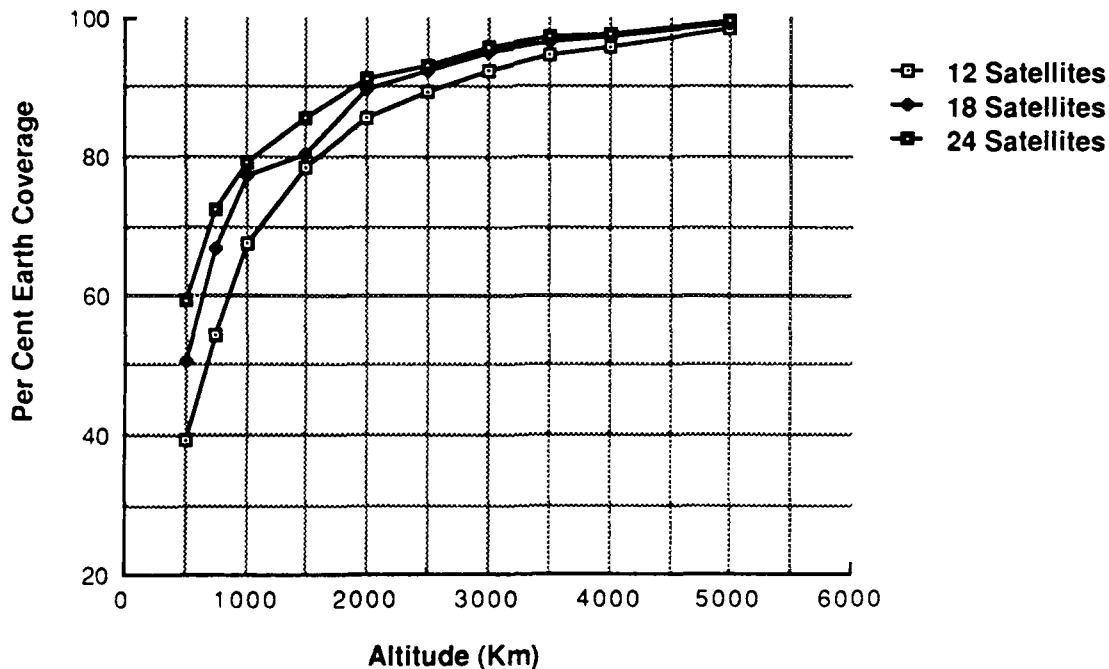
**Fig. 5-4 LEO Global Coverage**  
For  $i=30$ , 3 Satellites Per Plane



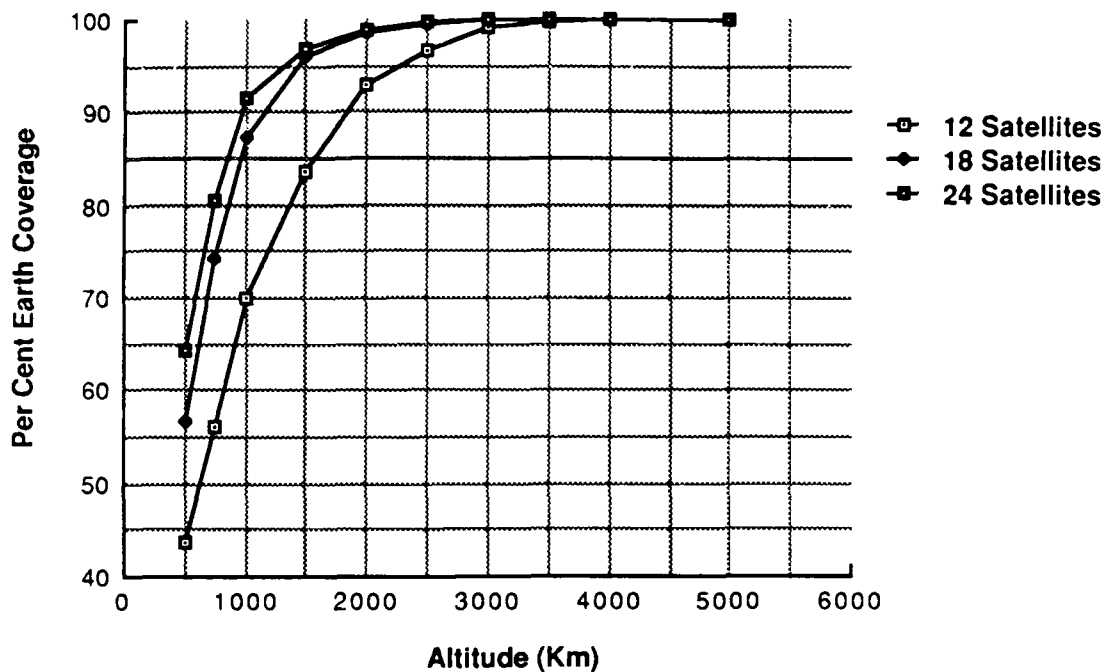
**Fig. 5-5 LEO Global Coverage**  
For  $i=45$ , 3 Satellites Per Plane



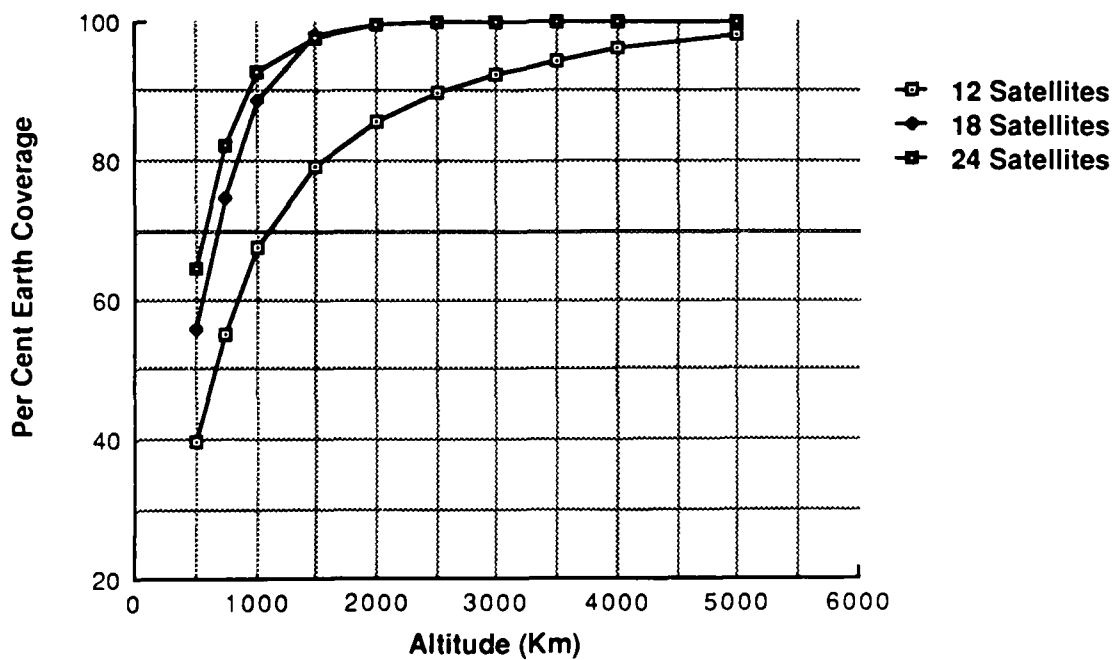
**Fig. 5-6 LEO Global Coverage**  
For  $i=60$ , 3 Satellites Per Plane



**Fig. 5-7 LEO Global Coverage**  
For  $i=30$ , 6 Satellites Per Plane



**Fig. 5-8 LEO Global Coverage**  
For  $i=45$ , 6 Satellites Per Plane



**Fig. 5-9 LEO Global Coverage**  
For  $i=60$ , 6 Satellites Per Plane

### Required Transmit Power Evaluation.

The required transmit power model developed in Chapter IV was used for this evaluation. The following assumptions were made in the model:

1. Free space loss was included in the model.
2. All antenna gain and beamwidth relationships were based on a parabolic reflector antenna.
3. All transmit distances were set to the maximum slant range occurring at a given altitude.
4. All antenna beamwidths were set to maximize earth coverage at a given altitude. This provided the geometry to calculate maximum slant range and provided a value to calculate the needed parabolic reflector antenna diameter.
5. Atmospheric attenuation was not included in the model.
6. Provisions for an anti-jam capability were not included in the model.

All calculations were based on a maximum satellite transmit frequency of 270 MHz (39:15). The bit rate, represented by  $B_m$  in the model, was set equal to 2600 bits per second (7:2-4). The  $(G/T)/(E_b/N_0)$  ratio was based on -31.9 dB at a bit error rate of  $10^{-3}$  (7:2-4). Using the -31.9 dB value in the model required changing the value back to a true ratio. By dividing -31.9 by 10 and taking the base 10 antilog, the true ratio of  $6.4564(10^{-4})$  was obtained. This is the value used for the  $(G/T)/(E_b/N_0)$  ratio in the model.

A Fortran program was used to calculate the required transmit power at the various altitudes. Fig. 5-10 displays these results. Note that the FLTSATCOM transmit power is based on an approximation made by the model. Altitude was not varied for the FLTSATCOM calculation. It serves as a comparison for the alternative constellation designs' required transmit power. These calculations are based on the maximum slant range occurring at a given altitude. This applies to the various altitudes evaluated for the alternative constellation designs as well as FLTSATCOM at geosynchronous altitude.

The required transmit power model is very optimistic. For FLTSATCOM it calculates 20.72 dBm as the required transmit power. The actual transmit power is much higher. Radio frequency output power varies between 26.4 watts up to 42.5 watts for FLTSATCOM transmitters (39:13-15). The AFSATCOM transmitter puts out 31.7 watts (39:15). This is equivalent to 45.01 dBm. Since the AFSATCOM output power level lies between the minimum and maximum output power on FLTSATCOM, it will be used as a baseline for comparisons. The difference between the calculated value and the actual value amounts to about 24 dBm. This difference will be attributed to those effects not taken into account in the model. These effects are mainly comprised of atmospheric attenuation and anti-jam capabilities. The figure of 20.72 dBm will be used for comparison.



From Fig. 5-10 altitudes above about 2500 km require more transmit power than is currently available on FLTSATCOM. This power limitation is important since all alternative design satellites are based on the FLTSATCOM design. The only difference is the elimination of the apogee kick motor from the alternative design satellites.

Other considerations concerning satellite power generation are important. This analysis did not take into account the effects of lower earth orbits on the power generating capability of the satellite. Lower earth orbits move in and out of the earth's shadow more often than geosynchronous orbits. This may burden the power generation system since batteries must be used and recharged more often.

#### Selection of Constellation Designs for Further Study

Through consideration of the required transmit power calculations, displayed in Fig. 5-10, and the results of the tradeoff study, displayed in Figures 5-1 through 5-9, two specific alternative satellite constellation designs were selected for sensitivity study. These alternative designs were constellations with orbit inclinations of 45 and 60 degrees, two satellites per plane and an altitude of 2500 km.

These particular designs exhibited good coverage at 2500 km (see Figures 5-2 and 5-3). Additionally these designs showed some coverage sensitivity to the number of satellites in the constellation. In comparison, constellations with orbit inclinations of 45 and 60 degrees and six satellites

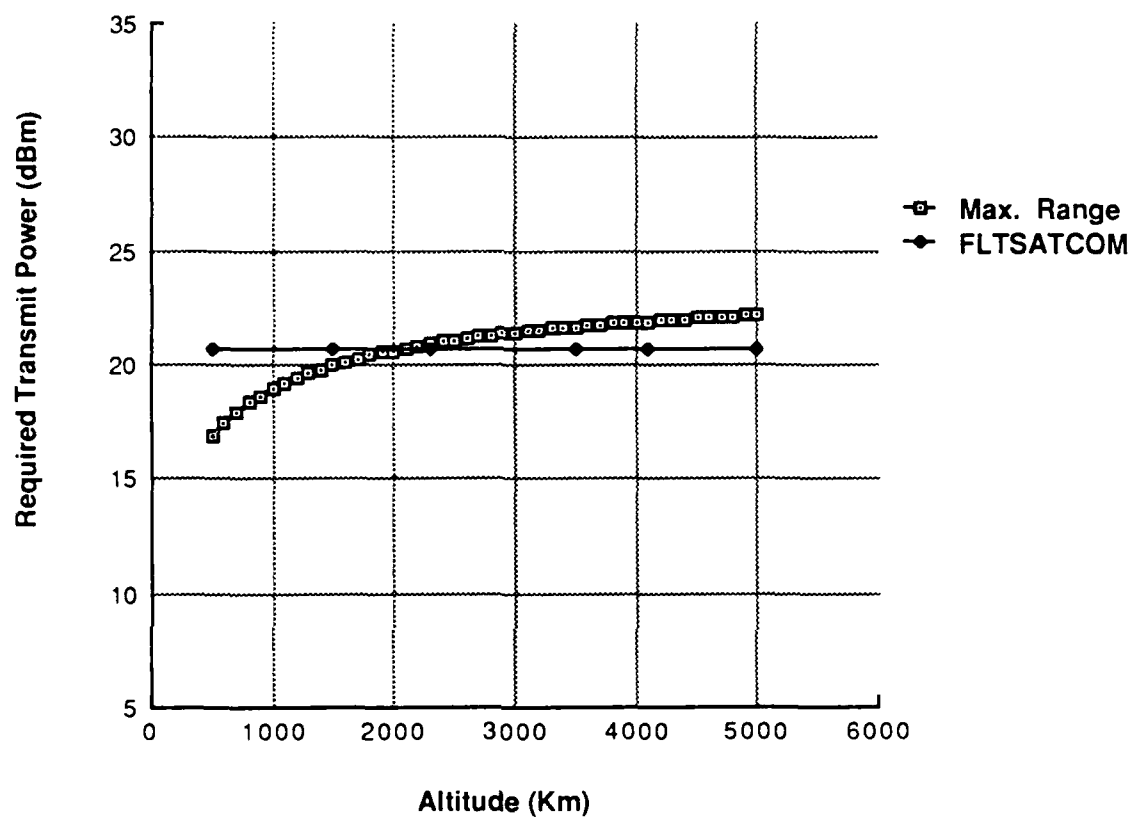


Fig. 5-10 Required Transmit Power

per plane exhibited similar results (see Figures 5-9 and 5-10). However, these designs offer only two orbital planes for the 12 satellite constellation. This results in somewhat poorer coverage for the 12 satellite, six satellites per plane design than the 12 satellite, two satellites per plane design. For this reason the alternative designs having two satellites per plane and inclinations of 45 and 60 degrees were selected for the sensitivity analysis.

#### Earth Coverage Sensitivity to Satellite Losses.

The constellation designs selected from the tradeoff and required transmit power analysis were used in the earth coverage sensitivity study. This analysis measures the effectiveness of a satellite communication constellation suffering satellite losses. The measure of effectiveness used was the per cent earth coverage provided by the constellation. The relationship of interest is how earth coverage degrades as satellites are removed from the constellation. Three regions were evaluated: global, the Mideast theater and the European theater.

Mechanics of analysis. The SAP/SATCOV routine was used for this phase of study. In each configuration, satellites were removed and a per cent of earth coverage was obtained. Satellites were removed by orbital planes. For example in the 12 satellite constellation, the first satellite was removed from a given plane. The second and subsequent satellites to be removed would be from the same plane until

it was empty. The procedure was continued until all satellites were removed from all the orbital planes. Depending on how many satellites were in the constellation, computer runs were made after every one, two or three satellites were removed to obtain a measure of earth coverage. Use of this approach was intended to produce a worst case scenario for satellite losses.

Global coverage. Figures 5-11 and 5-12 show how global coverage changes with respect to the number of satellites lost. Each plot shows the curve for the FLTSATCOM configuration, and the specified parameters for the alternative 12, 18 and 24 satellite constellations with the specified inclinations and number of satellites per plane. The curves for the FLTSATCOM constellation are based on their geostationary orbits (orbit inclination equals zero). For simulation runs involving FLTSATCOM, satellites were placed at 100°W, 71.5°E, 23°W, 172°E, and 93°W longitude (23:2).

Mideast theater. The region defined for this theater was from 5 degrees north latitude to 45 degrees north latitude. Longitude ranged from 10 degrees east to 65 degrees east. Figures 5-13 and 5-14 show how Mideast theater coverage varies with satellite losses for FLTSATCOM and the alternate system designs.

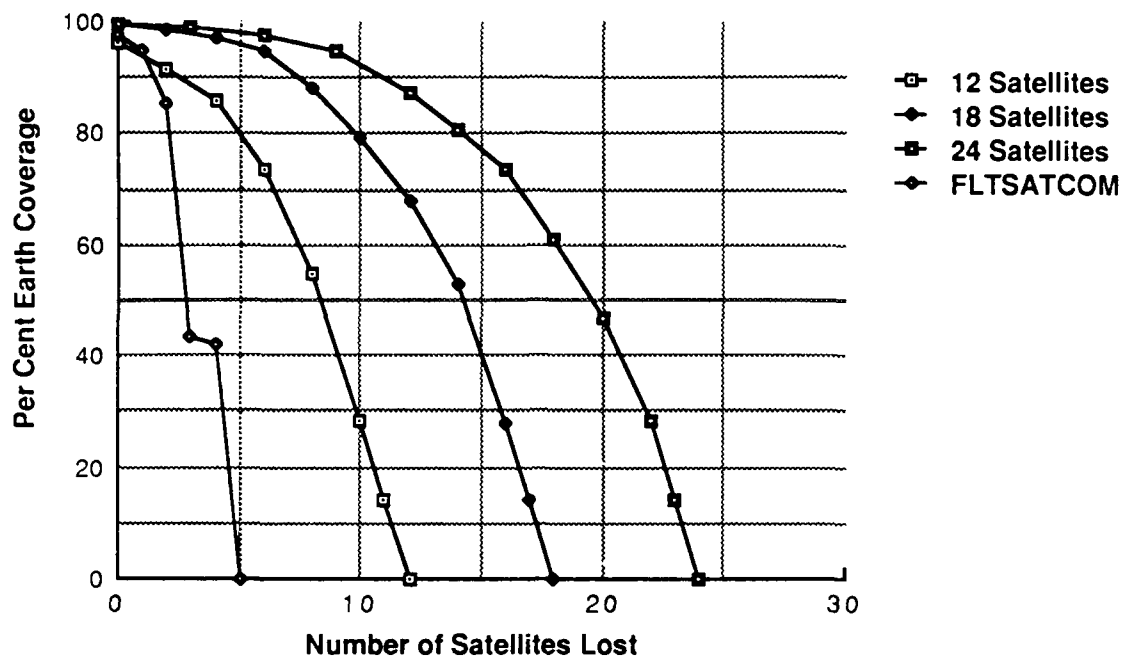


Fig. 5-11 LEO Global Coverage Sensitivity  
For  $i=45$ , 2 Satellites Per Plane, 2500 km

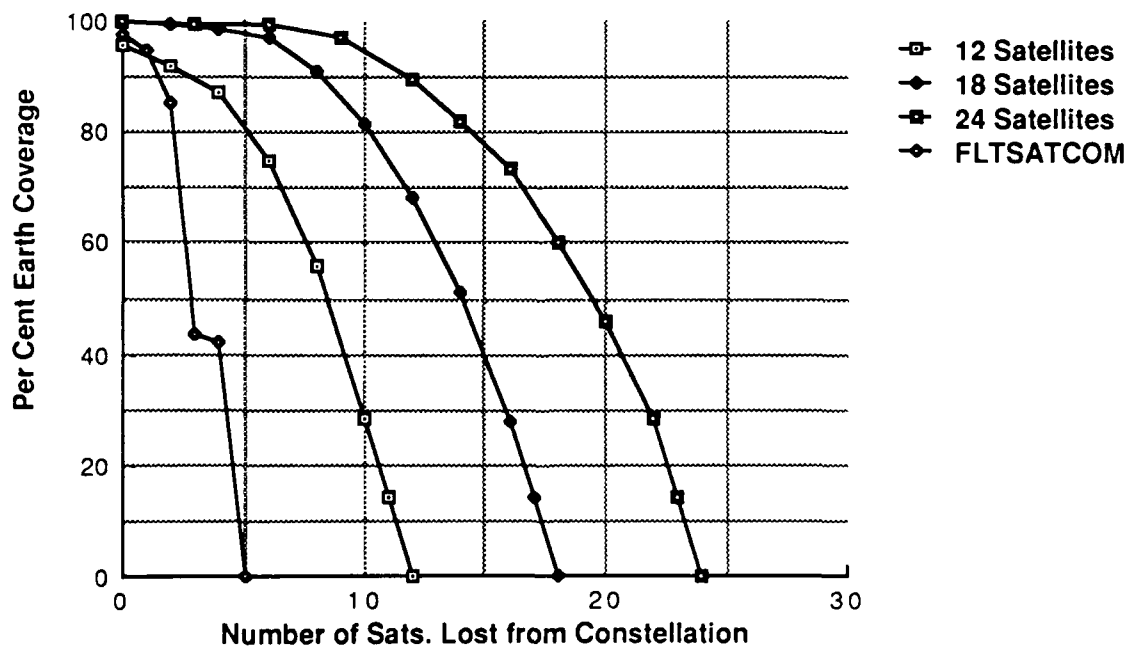
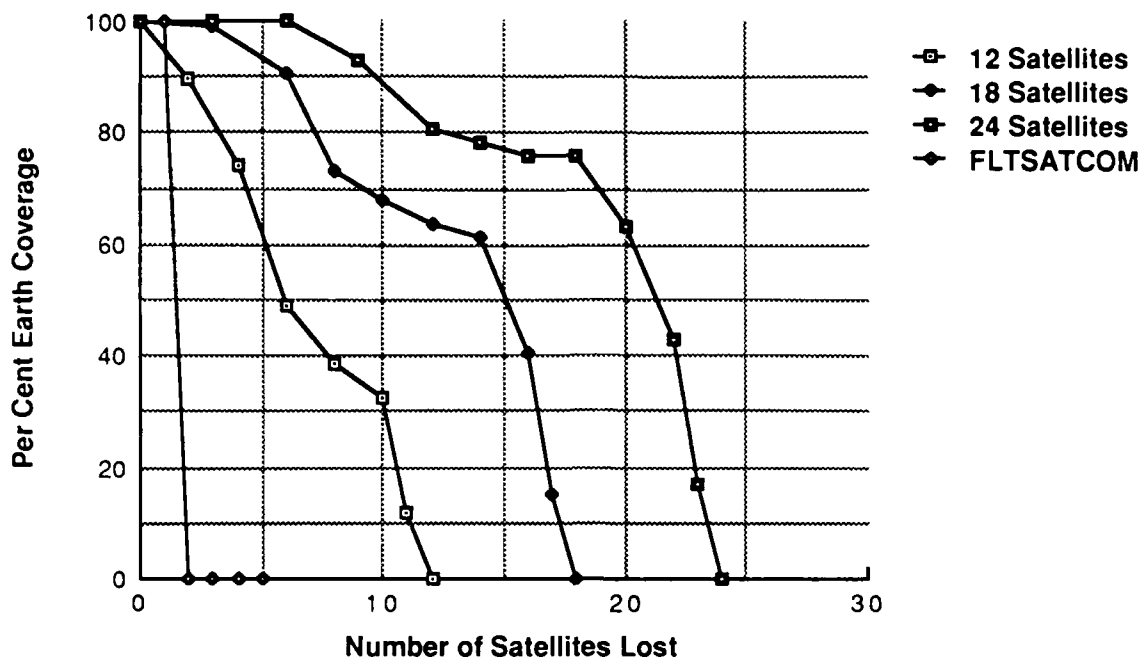
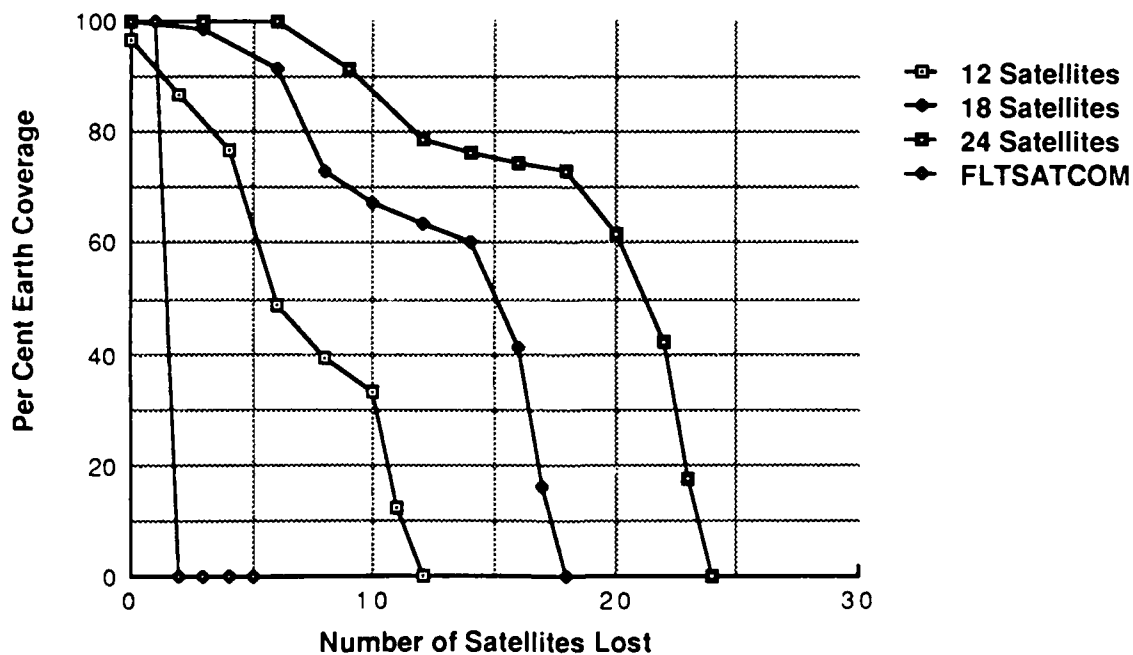


Fig. 5-12 LEO Global Coverage Sensitivity  
For  $i=60$ , 2 Satellites Per Plane, 2500 km



**Fig. 5-13 LEO Mideast Theater Coverage Sensitivity**  
For  $i=45$ , 2 Satellites Per Plane, 2500 km



**Fig. 5-14 LEO Mideast Theater Coverage Sensitivity**  
For  $i=60$ , 2 Satellites Per Plane, 2500 km

European theater. The region defined for this theater was from 35 degrees north latitude to 60 degrees north latitude. Longitude varied from 10 degrees west to 30 degrees east. Figures 5-15 and 5-16 show how European theater coverage varies with satellite losses for FLTSATCOM and the alternate system designs.

#### Low Earth Orbit Constellation Performance Limitations

The alternative constellation satellites were assumed to have the same basic design as a FLTSATCOM spacecraft. The only difference was the elimination of the apogee kick motor for the alternative designs. Additionally it was assumed that no modifications to current UHF MILSATCOM user equipment were made. These system design limitations caused several performance limitations in the alternative constellation designs. However, the force structuring concept presented in the alternative constellation designs also offered some performance improvements.

Applying the system design limitations to the low earth orbit constellation designs causes two performance limitations. These are communication range and ground based antenna tracking requirements. Without intersatellite links and a complicated control system, the range or footprint of lower earth orbit satellites is much less than that provided by a geosynchronous satellite. SAP/SATCOV results show that a geosynchronous satellite with antenna beamwidth set to maximize earth coverage covers about 42 per cent of the

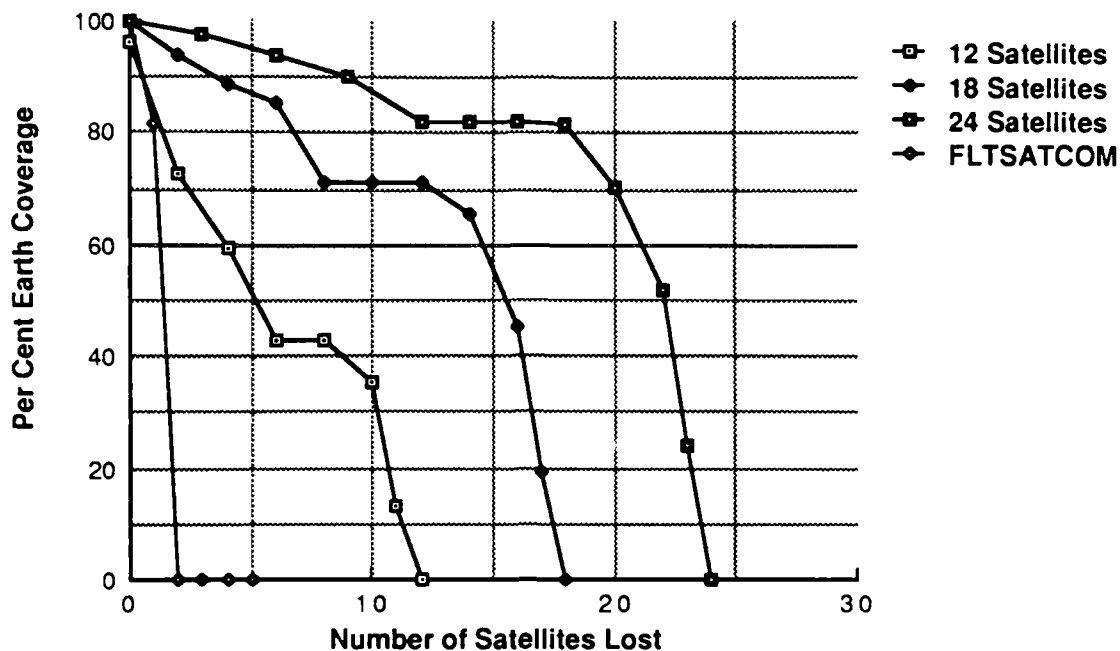


Fig. 5-15 LEO European Theater Coverage Sensitivity  
For  $i=45$ , 2 Satellites Per Plane, 2500 km

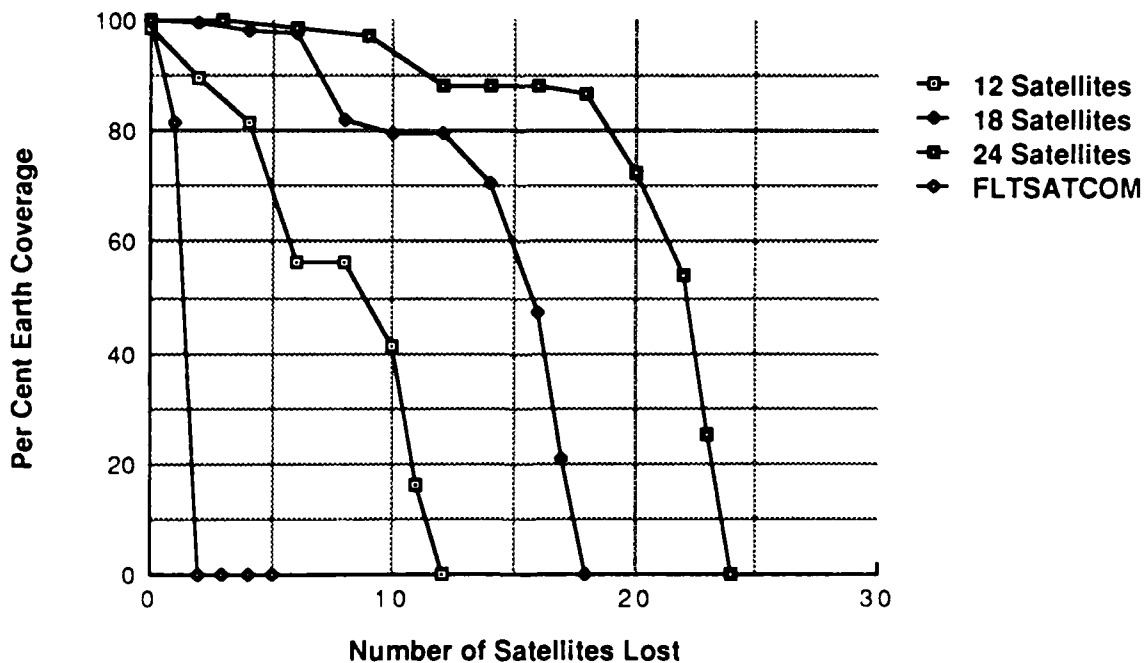


Fig. 5-16 LEO European Theater Coverage Sensitivity  
For  $i=60$ , 2 Satellites Per Plane, 2500 km



earth's surface. This represents a much larger footprint than satellites in the 500 to 5000 km altitude range. Fig. 5-17 shows the maximum transmit distance for low earth orbits and higher orbits. These maximum distances represent the distance across the satellite's footprint at its widest point.

Another performance limitation caused by the low earth orbit is a ground antenna tracking requirement. As the satellites orbits become lower, satellites no longer remain fixed in the sky as they do in stationary orbits. For the low flying constellation, a ground antenna would need to "lock-on" and track a satellite to make contact with it. Current FLTSATCOM user equipment does not have this capability. For instance the current ship board UHF antennas are only steerable. This means the antenna does not possess the capability to track a satellite. The antennas do possess an azimuth gyro stabilized platform. Elevation is adjusted manually (24).

Advantages of Low Earth Circular Orbits. The alternative constellations of 12, 18 and 24 satellites do offer a significant increase in earth coverage during attrition of satellites as compared to FLTSATCOM. Additionally a much larger channel capacity exists since each satellite in the alternative constellations possessed the same design as a FLTSATCOM satellite. However, to implement a low earth orbit FLTSATCOM replacement system under the design limitations

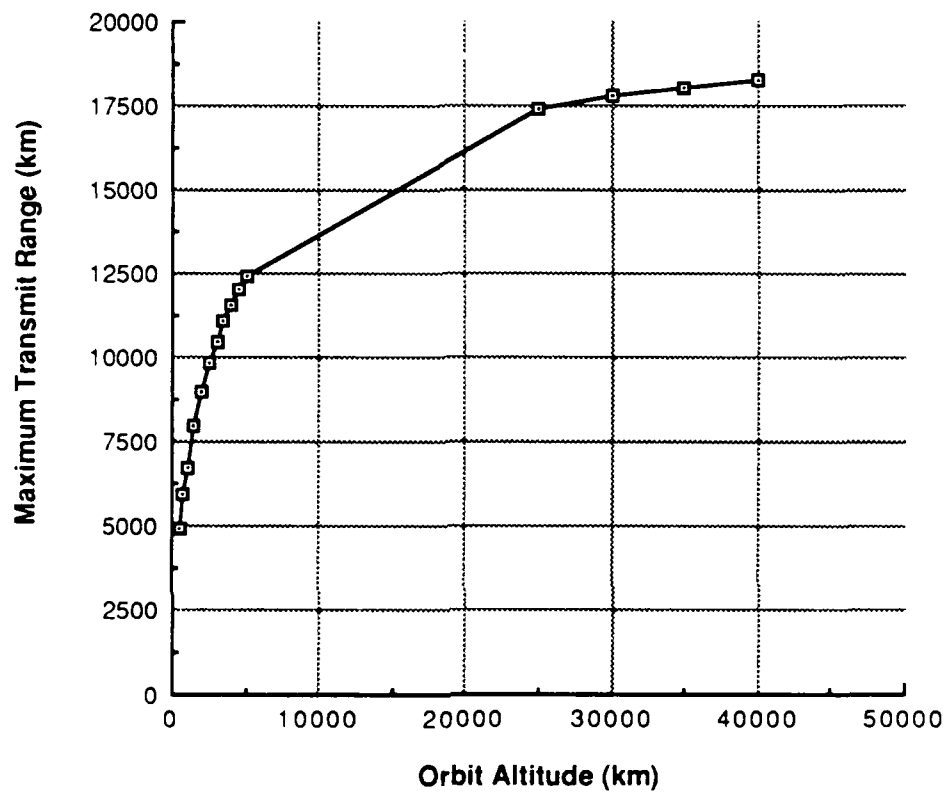


Fig. 5-17 Maximum Transmit Range

noted earlier is not possible. These low earth orbit constellations will require the next generation communication technology.

These results indicated a change in constellation design was needed to satisfy system design limitations. This design should be compatible with current user equipment and provide communication range comparable to the current FLTSATCOM constellation. One possible orbit offering this capability is the 12 hour Molniya orbit. This is a highly elliptical orbit with a perigee of about 400 km and an apogee of 4000 km. The Soviets use these orbits to provide long distance communication links over their country (20:58).

#### Molniya Constellation

The Molniya constellation investigated in this analysis used 12 satellites. The same satellite design considerations were assumed. This included the same features as the FLTSATCOM spacecraft but with no apogee kick motor(AKM). Injection into this orbit requires more energy than low earth orbits but less than that required by geosynchronous orbits. If detailed analysis shows that an AKM is needed, the cost can be included in the launch cost calculations by adjusting the launch cost per pound.

Molniya constellation design parameters. A total of six orbital planes was used. Each plane contained two satellites phased 180 degrees apart in the orbit. No relative phasing of the satellites was used. Three orbital planes were

situated with apogees over the northern hemisphere. The other three orbital planes were situated with apogees over the southern hemisphere. For the northern hemisphere orbits, ascending nodes were placed at 0, 120 and 240 degrees east longitude. Southern hemisphere orbit ascending nodes were placed at the same locations. Orbital plane characteristics were borrowed from the Soviet Union's Molnya constellation. This placed the perigee at 454 km and the apogee at 39903 km. All orbital planes were inclined at 63 degrees (20:232).

Global coverage results. The constellation design parameters were input to the SAP/SATCOV routine. As a first estimate antenna beamwidth was set to maximize earth coverage at 20000 km altitude.

The constellation provided excellent global coverage. All ground points were always in view of at least one satellite in the constellation (100 per cent coverage). This compares with a 97 per cent global coverage by the FLTSATCOM constellation. Additionally the constellation provided 98.2 per cent double satellite coverage and 88.1 per cent triple satellite coverage. Results showed the satellites to be useful during about 8 to 8.5 hours of their 12 hour orbit. During this 8 to 8.5 hour window, satellite altitude varied from about 24000 km to 39903 km (apogee). Their locations with respect to the earth varied 6.4 degrees in longitude and 16.3 degrees in latitude during the useable time window. This region is defined by the area on the earth's surface that a ray from the center of the earth to the satellite

traces out as the satellite moves through its orbit during the useable time window.

Required transmit power. Required transmit power calculations were made using the model presented in Chapter IV. Antenna beamwidth was calculated to maximize earth coverage at 24,000 km altitude. Results from SAP/SATCOV showed this altitude to be the minimum altitude during the satellite's useable 8 hour time period. This 8 hour window is a result of the highly elliptical orbit. During the other 4 hours, the satellite's orbital velocity is much higher as a result of lower orbital altitudes. The satellite's footprint decreases considerably during this perigee passage. Due to the small footprint and high orbital velocity, the satellite is not useful for communications during this 4 hour, perigee passage time period.

Required transmit power calculations were based on the same  $(G/T)/(E_b/N_0)$  ratio used previously. Slant range was calculated using the apogee altitude of 39903 km. Results showed the maximum required transmit power to be 23.2 dBm. This is slightly higher than the calculated FLTSATCOM available transmit power. This difference may require a power generation system modification or operation with less than the calculated transmit power margin.

Global coverage sensitivity to satellite losses. To evaluate global coverage sensitivity to satellite losses, the SAP/SATCOV routine was used. Each run removed one or two satellites from the constellation. Satellites were removed to eliminate orbital planes. Removal of orbital planes was rotated between the northern and southern hemisphere orbits. This procedure was intended to produce a worst case scenario. Fig. 5-18 shows the global coverage sensitivity to satellite losses for both the Molniya constellation and FLTSATCOM.

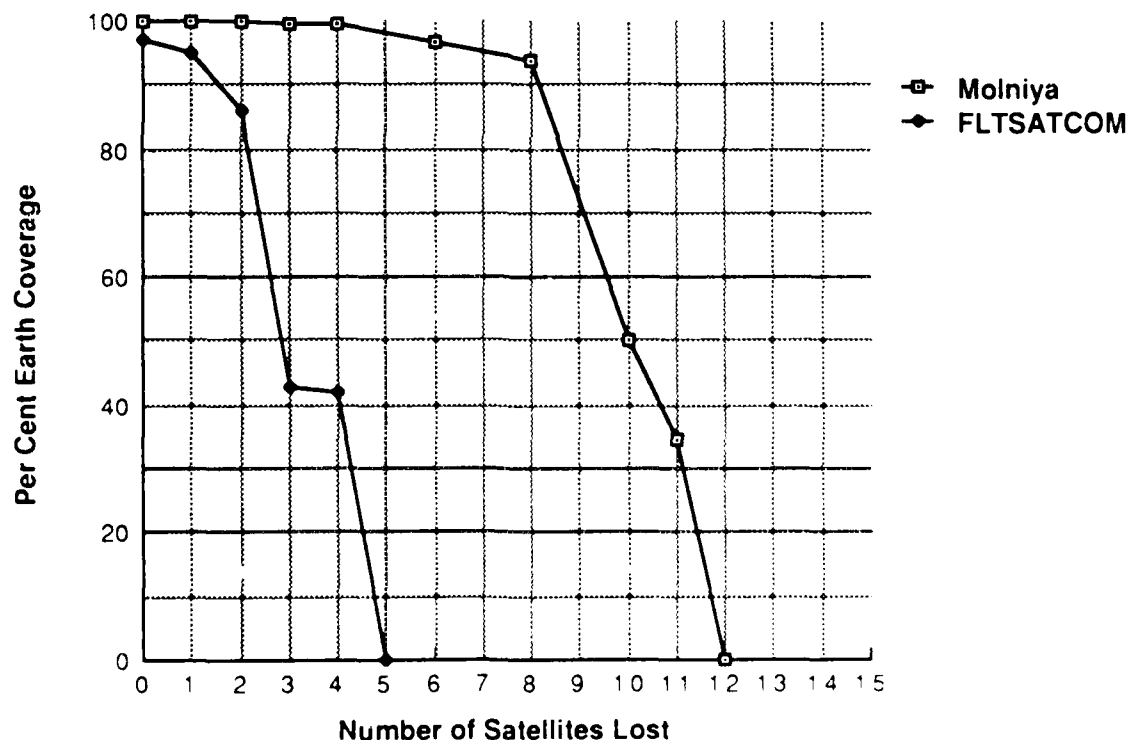


Fig. 5-18 Molniya Global Coverage Sensitivity

Mideast theater coverage sensitivity. Fig. 5-19 shows how the Mideast theater coverage degrades as satellites are lost from FLTSATCOM and the Molniya constellations. The region used for the Mideast theater was as previously defined. Removal of satellites from the FLTSATCOM constellation, removed those satellites with theater coverage first. Removal of satellites from the Molniya constellation followed the same procedure. By using the results of the full, 12 satellite Molniya constellation, those satellites providing the greatest theater coverage were identified. These satellites were removed from the constellation first. Both of these procedures for removing satellites were intended to produce a worst case scenario.

European theater coverage sensitivity. Fig. 5-20 shows how the European theater coverage degrades as satellites are lost from both the FLTSATCOM and Molniya constellations. The region used for the European theater was as previously defined. The process for removing satellites from the constellations was as previously described.

Operational considerations. The Molniya constellation satellites are useable for about 8 hours out of their 12 hour period. They remain relatively fixed in the sky during this 8 hour time period. Additionally since their usefulness occurs at relatively high altitudes, their footprint provides good communication range.

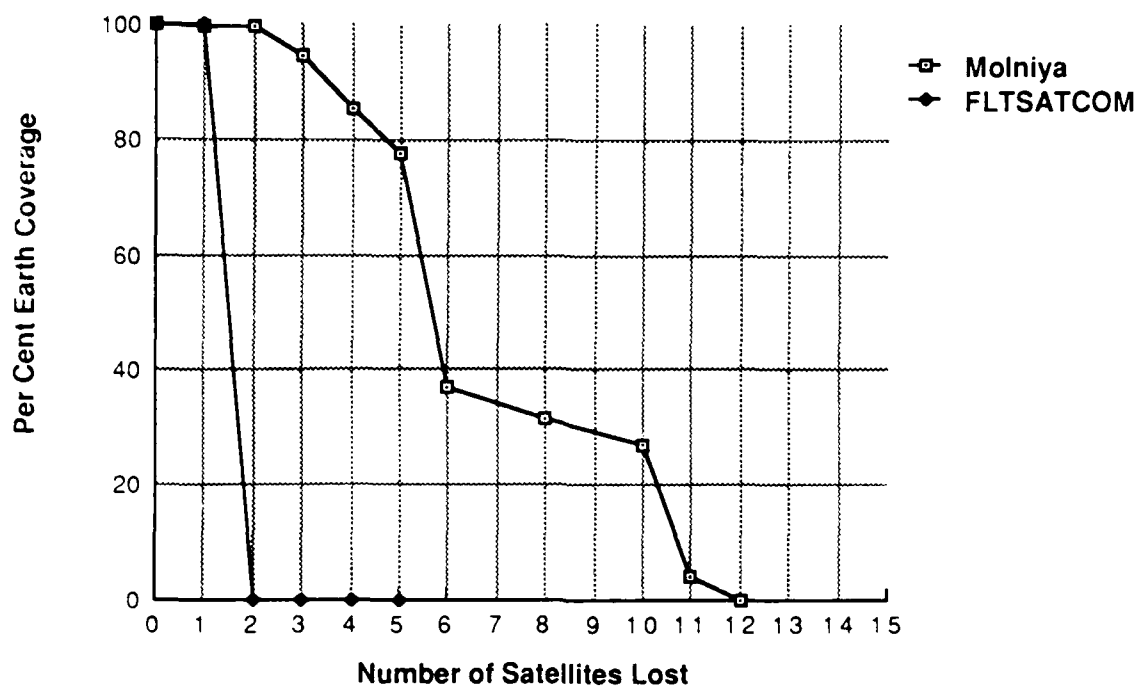


Fig. 5-19 Molniya Mideast Theater Coverage Sensitivity

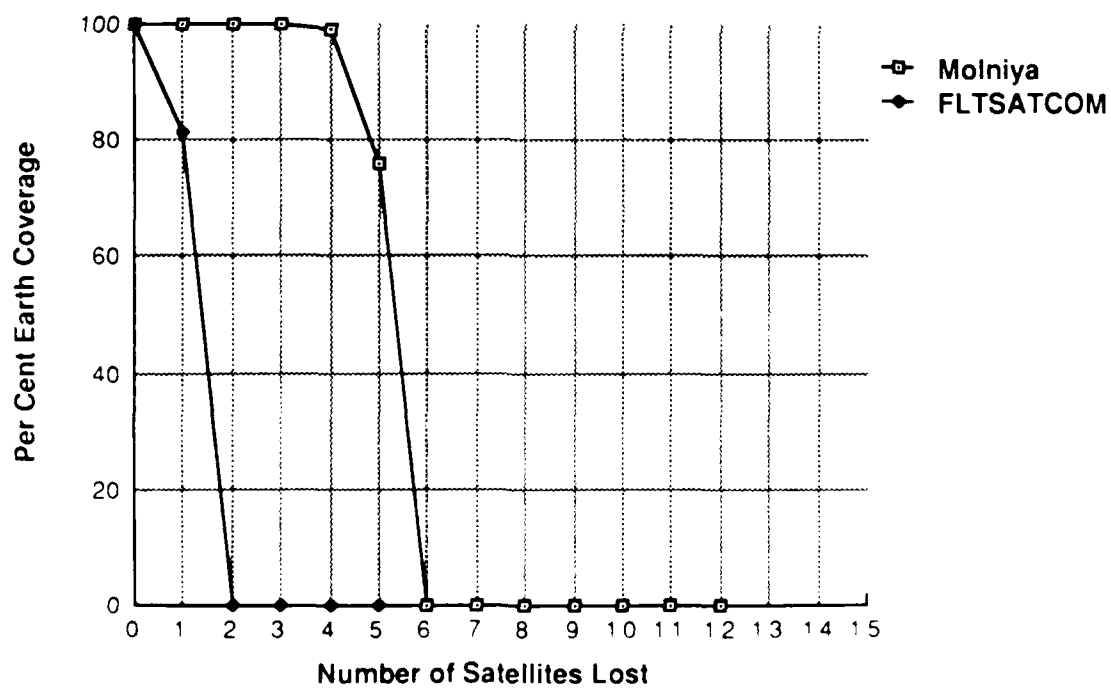


Fig. 5-20 Molniya European Theater Coverage Sensitivity



Basic structure modifications may be needed to enable the satellite to survive the perigee passages. Consideration must be given to possible atmospheric drag effects and acceleration forces. Drag may result from the low perigee altitude. Acceleration forces are due to the increased orbital velocity as the satellite approaches and passes perigee. These characteristics may require modifications to the attitude and velocity control system. One positive characteristic concerning Molniya orbits is noted by Nicholas Johnson. "Molnitya satellites do not need periodic station-keeping maneuvers because solar-lunar perturbation effects naturally retain the spacecraft in the vicinity of their nominal ascending nodes (65 and 245 degrees east longitude)" (20:65). These ascending nodes refer to those used by the Soviets in their Molniya constellations.

#### Cost Analysis Results

The cost model presented in Chapter IV was used. The model involved two parts. The first part applied learning effects to satellite fabrication costs. The second part accounted for launch costs.

Fabrication cost. Table 5-2 shows the cost breakdown for the alternative constellation satellites (36). These cost figures are based on the current FLTSATCOM satellite. The total unit fabrication cost is \$82,989,000. This figure will be used as the first unit fabrication cost for the alternative constellation designs.

Table 5-2 also provides the unit fabrication cost of the current FLTSATCOM satellite. This unit cost is equal to the alternative system satellite cost plus the cost of an apogee kick motor (\$3,486,000). The FLTSATCOM satellite unit fabrication cost is \$86,475,000. This value will be used as the FLTSATCOM unit fabrication cost in calculating FLTSATCOM system cost.

Launch costs. Since much uncertainty exists concerning future launch costs, launch costs will be parameterized. Launch costs will be represented in dollars per pound of payload (\$/lb) units. This requires an estimation of the satellite weight to obtain a per unit launch cost. Table 5-3 shows the breakdown of the alternative system satellite weight (39:8). These figures are based on actual FLTSATCOM satellite weight. Table 5-3 also shows the breakdown of the FLTSATCOM satellite weight (39:8). Note that the difference between the two satellites' weights is the 2049 lb apogee kick motor (39:8). The alternative system satellites do not include this apogee kick motor. For computational purposes the total liftoff weight for the alternative system satellites and the FLTSATCOM satellites were rounded to 2100 lbs. and 4150 lbs. respectively.

**Table 5-2 Satellite Fabrication Cost Breakdown**

<u>Satellite System</u>	<u>Cost (\$k)</u>
1. Satellite Support	5204
2. Integration/Assembly	1216
3. Structures	4249
4. Telemetry, Tracking & Command	3350
5. Attitude Velocity Control Ssystem	3652
6. Reaction Control System	2209
7. Electrical Power and Distribution	9457
8. Thermal	981
9. UHF Communications System	16821
10. SHF Communications System	2934
11. Payload Support Communications	316
12. System Test and Evaluation	7389
13. System Engineering	9251
14. Program Management/Data	12516
15. Launch Operations	3392
16. Initial Orbital Checkout	<u>52</u>
<b>Total Alternative System Satellite Unit Cost</b>	<b>82989</b>
<b>FLTSATCOM Satellite Unit Cost</b>	
17. Add Apogee Kick Motor	<u>3486</u>
<b>Total FLTSATCOM Satellite Unit Cost</b>	<b>86475</b>

**Table 5-3 Alternative and FLTSATCOM Satellite Weight**

<u>Satellite System</u>	<u>Weight (lbs)</u>
1. Structures	369
2. Thermal Control	33
3. Electrical Power and Distribution	721
4. Attitude and Velocity Control	131
5. Communications	496
6. Telemetry, Tracking and Command	56
7. Reaction Control	65
8. Hydrazine Propellant	189
9. Launch Vehicle/Payload Adapter	<u>44</u>
<b>Total Alternative System Satellite Weight</b>	<b>2104</b>
<b>FLTSATCOM Satellite Weight</b>	
10. Add Apogee Kick Motor	<u>2049</u>
<b>Total FLTSATCOM Satellite Weight</b>	<b>4153</b>

Total system cost. Fig 5-21 presents the FLTSATCOM system cost. Eight satellites have been produced. Eight boosters were also produced. However, there are only five operational satellites in the current FLTSATCOM constellation.

Fig 5-21 assumes no learning ( $S=1$ ) for the FLTSATCOM unit fabrication costs. System costs are shown for launch costs of 10, 15 and 20 thousand dollars per pound of payload. Current FLTSATCOM satellites cost approximately 20 thousand dollars per pound of payload to launch.

Fig 5-22 presents the total system cost for the alternative systems. This applies to both the low earth orbit constellations as well as the Molniya constellations. The curves shown on this figure assume no learning ( $S=1$ ) for the alternative system satellite fabrication costs. Total system costs for launch costs of 1, 5, 10, 15 and 20 thousand dollars per pound of payload are shown. Figures 5-23 and 5-24 show the same results except that learning rates of 0.95 and 0.90 respectively are applied to the unit fabrication costs.

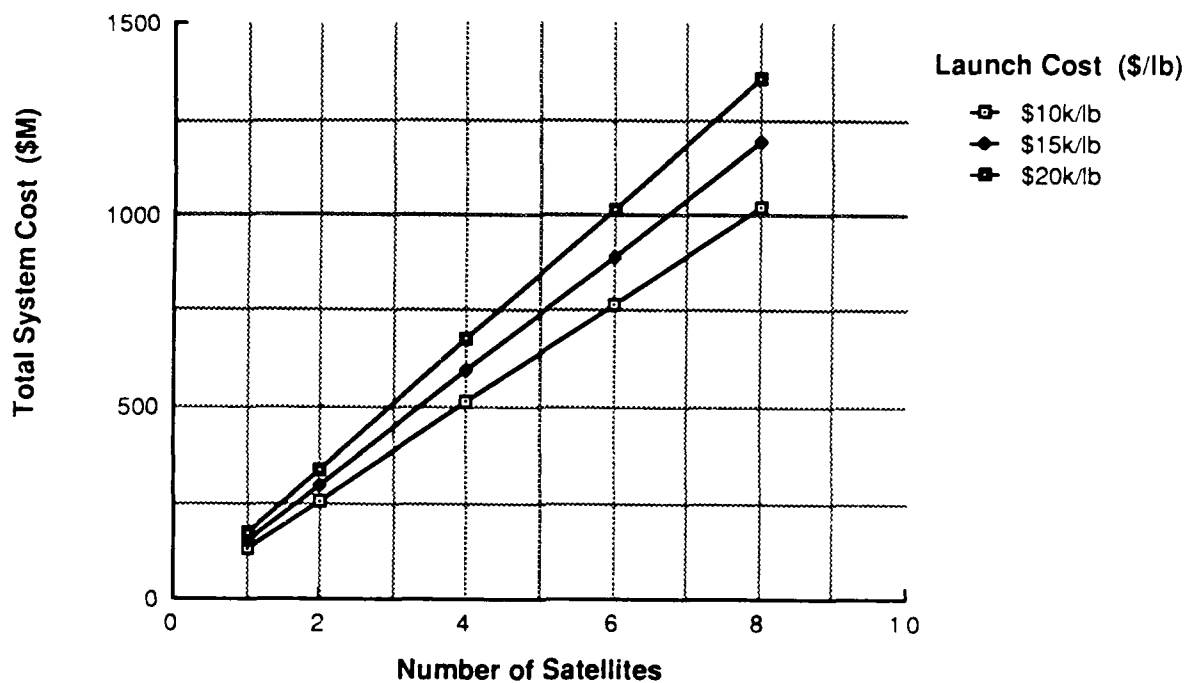


Fig. 5-21 FLTSATCOM System Cost, No Learning

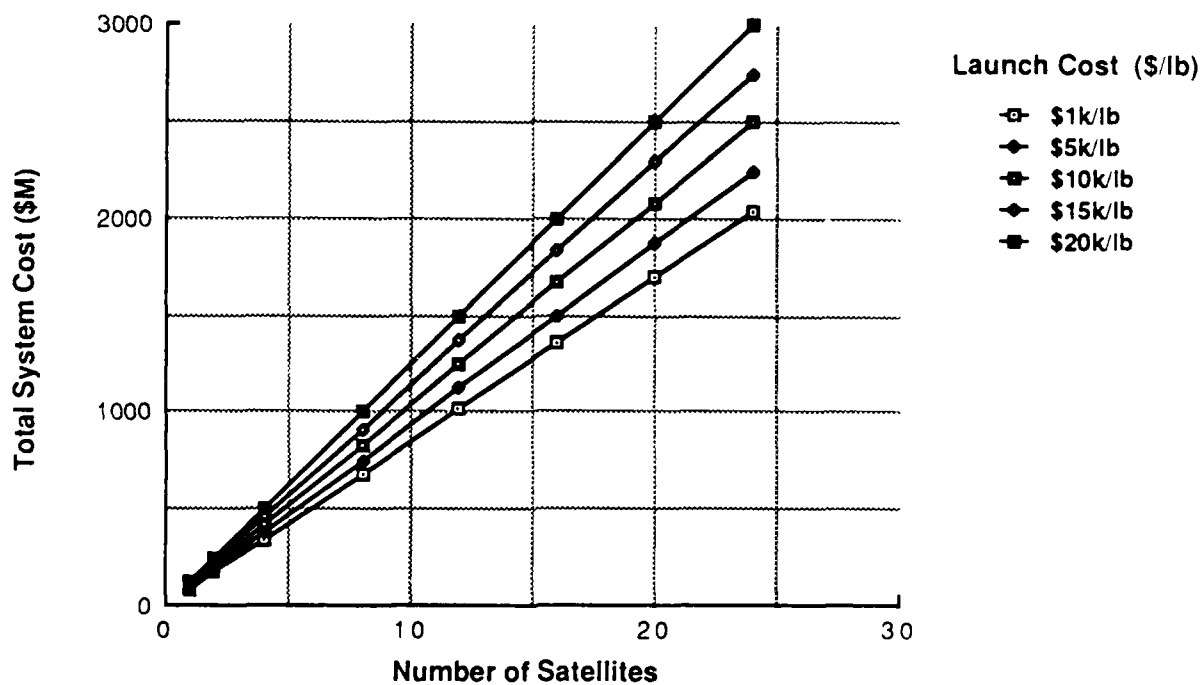


Fig. 5-22 Alternative System Cost, No Learning

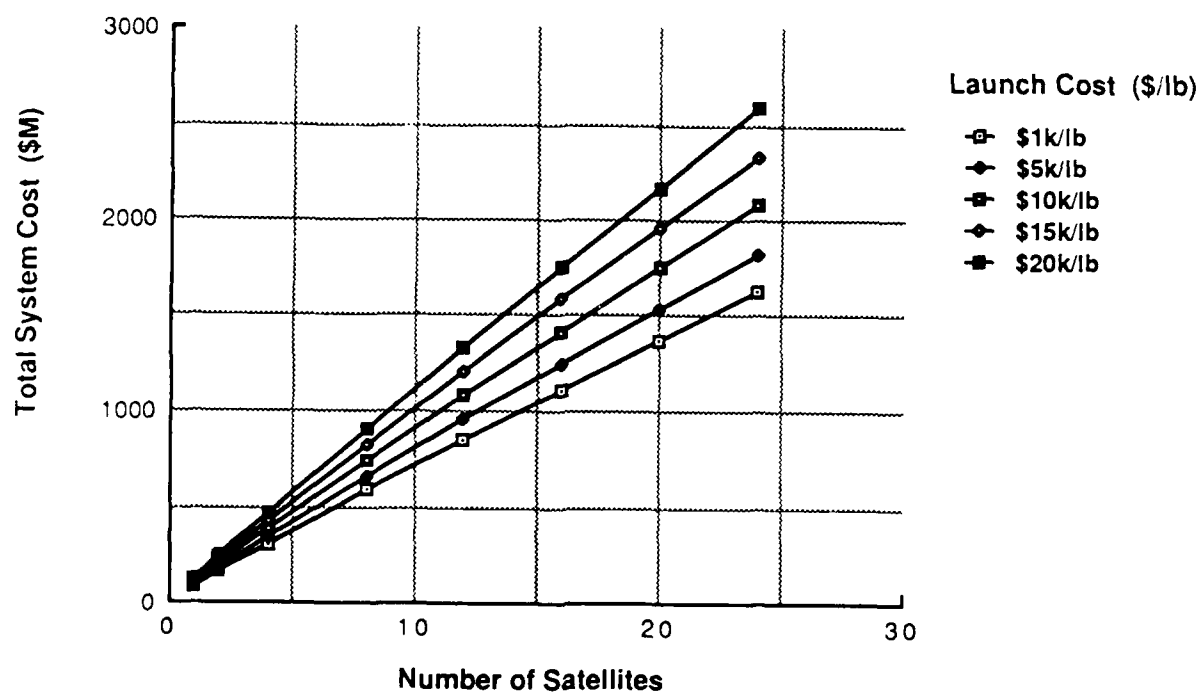


Fig. 5-23 Alternative System Cost, 0.95 Learning

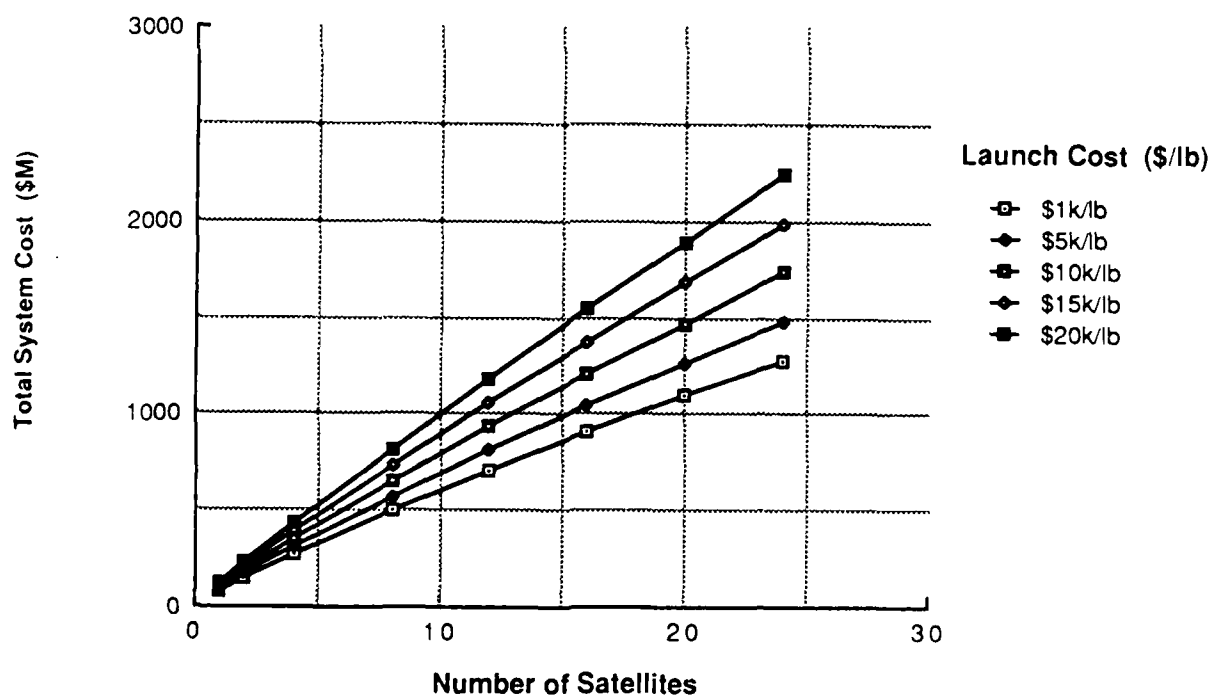


Fig. 5-24 Alternative System Cost, 0.9 Learning

## VI. Conclusions and Recommendations

An examination of the results presented in Chapter V reveals some interesting characteristics concerning the alternative UHF MILSATCOM force structuring strategies studied in this analysis. This chapter presents conclusions concerning low earth orbit (LEO) constellations and a Molniya constellation. Finally recommendations for further study and closing remarks are made.

### LEO Constellations

The use of LEO constellations as a compatible FLTSATCOM replacement presents several problems. Implementation of a LEO constellation (2500 km altitude) will require extensive design modifications to the present FLTSATCOM satellites as well as the current user equipment. One major reason for this is that at the lower altitudes, the satellite's footprint becomes smaller. If communication ranges greater than that provided by the LEO satellite's footprint are needed, the communication system will need intersatellite links or a complicated ground station link system. Either of these systems will require a complicated control system and extensive hardware development to the current FLTSATCOM design. Additionally, a tracking capability would be needed for the ground antennas. This requirement will require both hardware and software development. Some type of motor driven mechanism would be needed to allow the ground antennas to follow a LEO satellite across the sky. Tracking algorithm

software to determine satellite placement at a given time will be needed to initialize the ground to satellite link.

However, a system using a LEO proliferated design offers some significant advantages. System global and theater coverage sensitivity to loss of satellites improves significantly in the proliferated design. Fig. 6-1 shows how global coverage changes due to satellite losses. The figure shows curves for a twelve satellite LEO configuration ( $i=45$ , two satellites per plane, altitude=2500 km), the current FLTSATCOM constellation and the 12 satellite Molniya constellation. The alternative twelve satellite LEO constellation provides better global coverage than FLTSATCOM during satellite losses. Fig. 6-2 shows how European theater coverage changes due to satellite losses for the same constellation designs described above.

Fabrication and launch cost for an alternative proliferated LEO constellation will be higher than the current FLTSATCOM system. Cost comparisons shown in Chapter V were based on FLTSATCOM satellite costs. Since the FLTSATCOM system design is not feasible for a LEO constellation, significant communication system design and development would be needed. These added costs will certainly make the LEO constellations an expensive alternative to the current FLTSATCOM configuration.



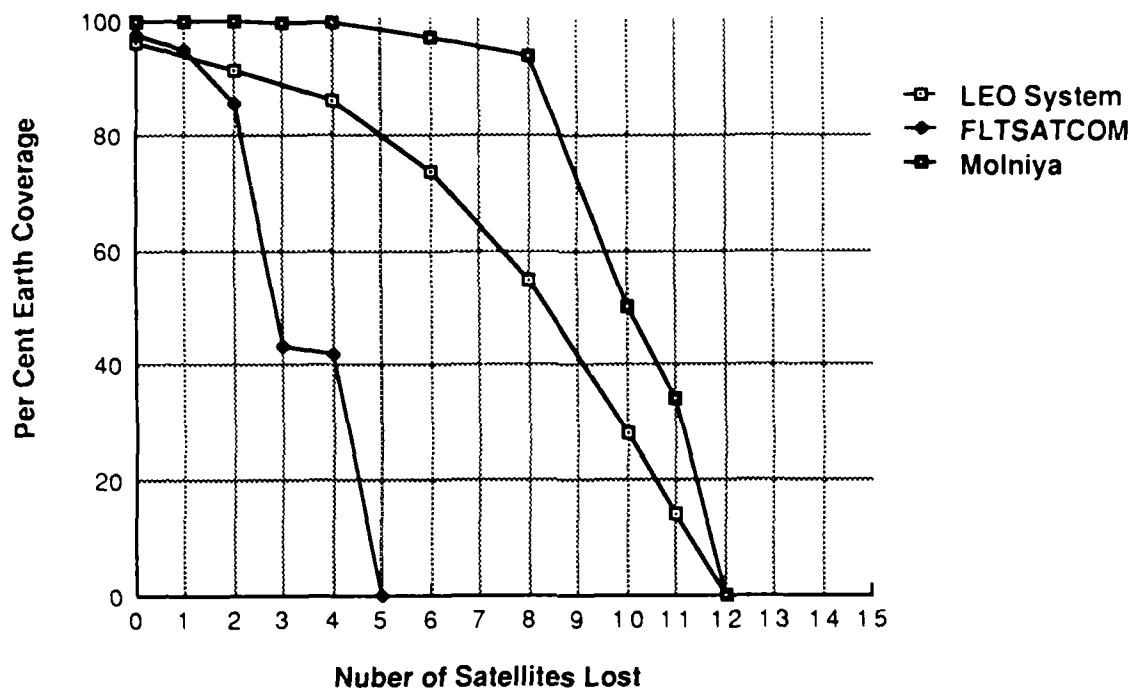


Fig. 6-1 Global Coverage Sensitivity Summary

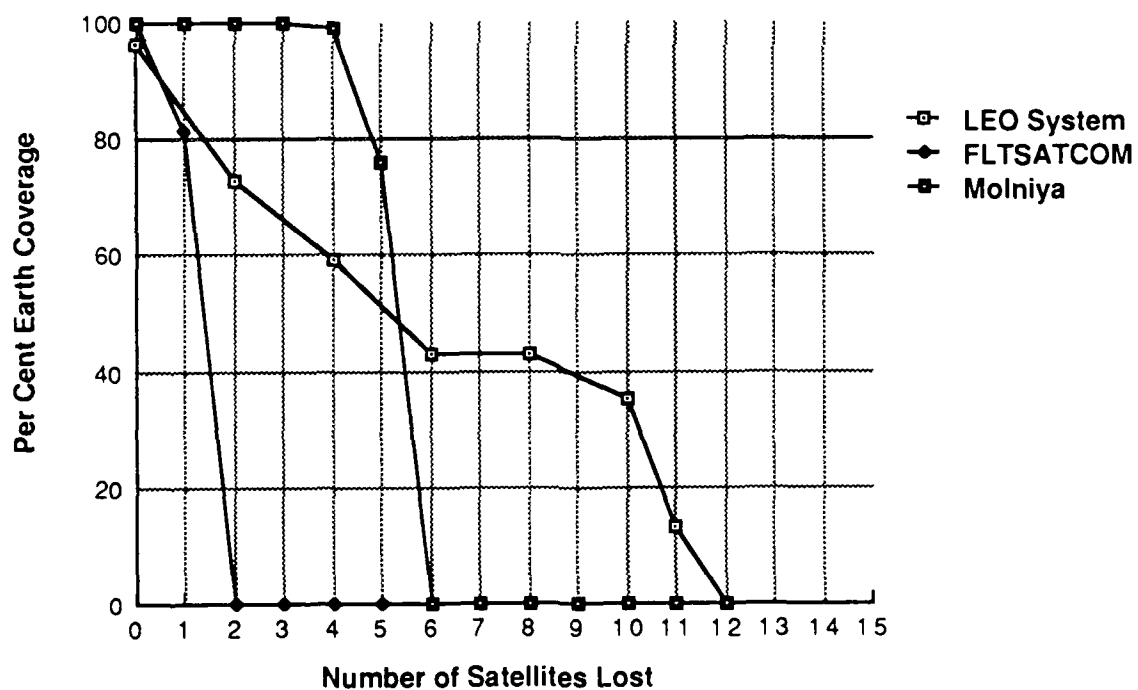


Fig. 6-2 European Theater Coverage Sensitivity Summary

### Molniya Constellations

The Molniya constellation consisting of twelve satellites appears to be a viable replacement FLTSATCOM system. Since satellites in the 12 hour, highly elliptical orbit are only useable for communications at altitudes between 24,000 and 40,000 km, a large footprint provides good communication range. These high altitudes result from the highly elliptical Molniya orbit. At altitudes of less than 24,000 km, the orbital velocity begins to change quickly while altitude decreases. This results in rapidly declining earth coverage as the satellite moves toward perigee. After passing perigee orbital velocity begins to decrease as altitude and thus coverage increase. Fig. 5-17 shows the maximum transmit distance (maximum footprint diameter) as a function of orbit altitude. FLTSATCOM provides communication for points within the footprint of one of its satellites. The comparably large footprint provided for by the Molniya constellation would also provide this capability. Also since the Molniya satellites are only operational during the high altitude portion of the orbit, the satellites remain relatively stable in the sky as viewed by a ground observer. Satellite movement may require a ground antenna tracking capability depending on the ground antenna beamwidth.

Power generation is of concern since results show the maximum transmit power for the Molniya satellites to be slightly higher than that available on the current FLTSATCOM

satellite. Modification of the power generation system or operation with a decreased power transmit margin may be required.

Molniya satellite structural design must consider the forces encountered during perigee passage. Orbital velocities change considerably during this time period, exerting forces on the spacecraft. Structural design must consider these effects.

The twelve satellite Molniya constellation provided superior global and theater coverage. This global and theater coverage is maintained during losses of satellites. Fig. 6-1 and Fig. 6-2 show FLTSATCOM and Molniya constellation global and European theater coverage sensitivity to satellite losses. Fig. 6-2 shows that FLTSATCOM European coverage degrades to 80 per cent after one satellite is lost while the Molniya constellation does not degrade to 80 per cent coverage until five satellites have been lost. In this respect the Molynia constellation is far superior to FLTSATCOM.

Cost estimates for the alternative satellites in the Molniya constellation are based on FLTSATCOM costs. The only difference is that the apogee kick motor has been eliminated from the alternative satellites. Fig. 6-3 compares FLTSATCOM and the alternative Molniya system costs. The FLTSATCOM cost curve is based on a launch cost of \$20k/lb. The Molniya constellation system cost is based on a launch cost of \$15k/lb. This cost represents a point between the

launch cost for LFO and geosynchronous orbits (17:5-6). Both cost curves assume no learning. The Molniya constellation system cost is very comparable to FLTSATCOM costs. The Molniya system's estimated cost is about four per cent more than the FLTSATCOM system cost.

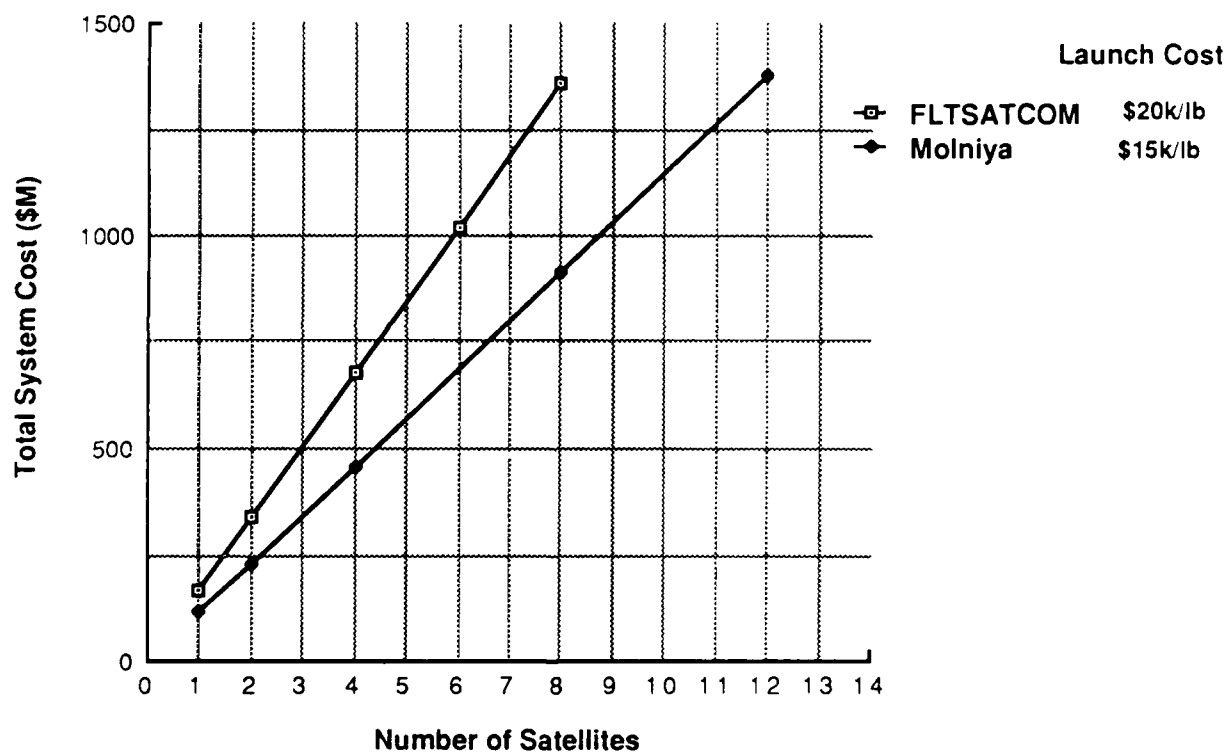


Fig. 6-3 FLTSATCOM and Molniya System Cost  
No Learning

Table 6-1 summarizes and compares the capabilities and cost of the FLTSATCOM system with the alternative constellation designs examined in this study.

Table 6-1 Alternative System Capabilities Summary

CHARACTERISTIC	ALTERNATIVE SYSTEM	
	LOW EARTH ORBIT CONSTELLATION	MOLNIYA CONSTELLATION
FLTSATCOM COMPATIBILITY	NO	YES
GLOBAL COVERAGE SENSITIVITY TO SATELLITE LOSSES	BETTER THAN FLTSATCOM	BEST OF ALL
THEATER COVERAGE SENSITIVITY TO SATELLITE LOSSES	BETTER THAN FLTSATCOM	BEST OF ALL
FABRICATION AND LAUNCH COST	HIGHER THAN FLTSATCOM	COMPARABLE TO FLTSATCOM

### Recommendations for Further Study

A determination of whether LEO or Molniya orbits provide better protection against anti-satellite weapons would offer a very useful piece of information to a decision maker. These relative advantages and disadvantages would help decision makers decide whether to pursue advanced communications technology for LEO systems or pursue the use of a Molniya constellation.

Further analysis is needed concerning the implications of LEO and Molniya orbit systems on a communication satellite design. This concerns the structural, antenna and power generation system designs. The Molniya orbit may have significant impact on the structural and antenna designs, while the LEO system may impact the power generation system design.

As new launch systems mature and are fielded an examination of future launch costs would be extremely useful. Launch costs comprise a large portion of the total system fabrication and launch cost. Good launch estimates would be useful in alternative system design analyses.

### Closing Remarks

This analysis of alternative force structuring strategies was undertaken due to the United States heavy reliance on space-based communication assets. The analysis shows that with as little as one satellite loss from the FLTSATCOM constellation, theater coverage can suffer drastically.

The United States must consider communication satellites as viable targets during a conflict. This reality must be given careful consideration in future MILSATCOM system designs. This quote from Guilio Douhet sums it up best: "Victory smiles upon those who anticipate the changes in the character of war, not upon those who wait to adapt themselves after changes occur" (18:91).

## Bibliography

1. Benjamin, Ralph. "Analysis of Connection Survivability in Complex Strategic Communications Networks," IEEE Journal On Selected Areas In Communication, SAC-4: 243-253 (March 1986).
2. Bousquet, M. and G. Maral. Satellite Communications Systems. New York: John Wiley and Sons, 1986.
3. Brandt, Major General Thomas C. "Military Uses of Space," Air University Review, 10: 40-51 (November-December 1985).
4. Cain, Dr. Joseph. Class notes obtained from lectures in OPER 611, Cost Analysis for System Design, School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB, Ohio, August, 1987.
5. Chiang, Dalen T. and Ru-fang Chiang. "Relayed Communication via Consecutive-k-out-of-n: F System," IEEE Transactions On Reliability, 35: 65-67 (April 1986).
6. Department of Defense Space Policy, 10 March 1987, (unclassified).
7. Department of the Air Force, Air Force Communications Command (AFCC). AFSATCOM System Operating Policy and Procedures, Volume 1 User's Guide. Offut Air Force Base: AFCC Strategic Information Systems Division, 1 Nov 1986.
8. Fitzgerald, Major David J., Correspondence Concerning Research Paper Requirements. Directorate of Systems Integration, Logistics and Support. United States Air Force Command, Peterson AFB, Colorado, 23 June 1987.
9. Fitzgerald, Major David J. Effectiveness of the MILSATCOM Requirements Process. Air Force Research Report No. AU-ARI-85-11. Maxwell, Alabama: Air University Press, 1985.
10. Frank, H. and I. T. Frisch. "Analysis of Survivable Networks," IEEE Transactions On Communication Technology, 18: 100-107 (1970).
11. Friedenstern, I. T. "Analysis of Survivable Networks," IEEE Transactions On Communication Technology, 18: 100-107 (1970).



12. Gagliardi, Robert. Introduction to Communications Engineering. New York: John Wiley and Sons, 1978.
13. General Research Corporation. Satellite Analysis Program Library Training Manual. Contract F05604-83-C-0018, United States Air Force Space Command, Peterson AFB, Colorado, 1986.
14. General Research Corporation. Satellite Analysis Program (SAP) Library Version 3.0 Program Module Description. Contract F05604-83-C-0018, United States Air Force Space Command, Peterson AFB, Colorado, February, 1986.
15. Gray, Colin S. American Military Space Policy: Information Systems, Weapon Systems and Arms Control. Cambridge, Massachusetts: Abt Books, 1982.
16. Heffes, Harry and Anurag Kumar. "Stochastic Damage Models and Dependence Effects in the Survivability Analysis of Communication Networks," IEEE Journal On Selected Areas In Communications, SAC-4: 234-242 (March 1986).
17. Hord, R. Michael. CRC Handbook of Space Technology: Status and Projections. Boca Raton, Florida: CRC Press, Inc., 1985.
18. Hungerford, John B., Major, USAF. "Organization for Military Space: A Historical Perspective." Student Report 82-1235, Air Command and Staff College, Maxwell AFB, Alabama, 1982.
19. Johnson, Nicholas L., Advisory Scientist - Teledyne Brown Engineering. "Soviet Military Space Systems." Address to AFIT GSO-87D students. Air Force Institute of Technology (AU), Wright-Patterson AFB OH, 4 December 1986.
20. Johnson, Nicholas L. Soviet Space Programs 1980-1985. San Diego, California: American Astronautical Society, 1987.
21. Joint Chiefs of Staff. Memorandum of Policy No. 178: Military Satellite Communications Systems. Washington: 17 March 1975, second revision 4 September 1986.
22. Koelle, Dietrich E. "Cost Reduction Trends In Space Communications By Larger Satellites/Platforms," Acta Astronautica, 11: 785-794 (December 1984).

23. Kopf, Capt T. J. "A Review of AFSATCOM." Research paper for EENG 421, Satellite Communication Systems, Dr Darrell G. Hopper, Fall 1986, pp. 77-85.
24. Latullippe, Phil, Civilian Employee of the Department of The Navy. Telephone Interview. Naval Space Command, Dahlgren, Virginia, 17 August 1987.
25. Manger, Warren P. and Harold O. Curtis. "Simplified Parametric Cost Trade-Offs In Satellite System Design," Acta Astronautica, 11: 795-802 (December 1984).
26. Molette, P. and others. "Technical and Economical Comparison Between A Modular Geostationary Platform and A Cluster of Satellites," Acta Astronautica, 11: 771-784 (December 1984).
27. Morrocco, John D. "Soviet Ground Lasers Threaten U.S. Geosynchronous Satellites." Aviation Week and Space Technology, 127: 27 (November 2, 1987).
28. Pratt, Timothy and Charles W. Bostian. Satellite Communications. New York: John Wiley and Sons, 1986.
29. Pritchard, Wilbur L. and Joseph A. Sciulli. Satellite Communication Systems Engineering. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1986.
30. Provan, J. S. and M. O. Ball. "The Complexity of Counting Cuts and Computing the Probability that A Graph Is Connected," SIAM Journal of Computers, 12: 777-778 (November 1983).
31. Raggett, R. J., editor. Jane's Military Communications 1987 (Eighth Edition). New York: Jane's Publishing Company, 1987.
32. Sears, Francis W. and others. University Physics. Reading, Massachusetts: Addison-Wesley Publishing Company, 1977.
33. Schrader, Robert L. Electronic Communication (Second Edition). New York: McGraw-Hill Book Company, 1967.
34. Schultz, James B. "Communications Connectivity Through Space," C3I Handbook. Palo Alto, California: EW Communications, Inc., 1986.
35. Slater, J.N. and L.A. Trinogga. Satellite Broadcasting Systems Planning and Design. Chichester, England: Ellis Horwood Limited, 1985.

36. Space Division, Air Force Systems Command. Cost Data Summary Report for Contract F04701-82-C-0007 with TRW Electronics and Defense. Los Angeles Air Force Station, California, 10 July 1987.
37. Spilker, James J., Jr. Digital Communications by Satellite. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1977.
38. Thibodeaux, Dwight D. "Fleet Satellite System Series, Part I System Overview." Personal Notes as Instructor at Det. 1, 3423 Technical Training Squadron, Air Training Command, United States Air Force, 27 November 1985.
39. TRW. Fleet Satellite Communications Spacecraft. TRW Electronics and Defense, One Space Park, Redondo Beach, California 90278, January, 1983.
40. United States Space Command, Directorate of Systems Integration, Logistics and Support. "An Alternative Constellation Design for A MILSATCOM System," GSO-87D Thesis Topic No. 55.
41. Vandenkerckhove, Jean A. "Economics Of Telecommunications Space Segments," Acta Astronautica, 11: 745-770 (December 1984).
42. Wilkov, R. S. "Analysis and Design of Reliable Computer Networks," IEEE Transactions On Communications, COM-20: 660-678 (June 1972).

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The purpose of this study was to determine and examine alternative force structuring strategies for military satellite communication (MILSATCOM) systems. The study was undertaken due to the United States' reliance on relatively few, expensive satellites as critical communication links. Current anti-satellite weapons pose a definite threat to missions using this type of strategy. In response to this situation, proliferated MILSATCOM designs using low earth circular orbits and a highly elliptical (Molniya) orbit were defined and analyzed. The objective of this effort was to compare the proliferated alternative systems' performance and cost with a current MILSATCOM system. The Fleet Satellite Communication (FLTSATCOM) system was used as the baseline system for comparison.

For low earth circular orbit constellations, a constellation design parameter tradeoff analysis was accomplished. This tradeoff analysis along with a satellite transmit power model were used to identify specific constellations for further study. In addition, a highly elliptical constellation was also evaluated. This design was based on orbits used by the Soviet Union for communication satellites.

To assess system performance, alternative constellation earth coverage sensitivity to satellite losses was calculated. This measure of effectiveness was used to evaluate system performance in a hostile environment. The evaluation included global coverage sensitivity as well as the European theater and Mideast theater coverage sensitivities.

Overall, both alternative force structuring strategies provided superior earth coverage when subjected to satellite losses. This was especially evident in the European and Mideast theaters. The Molniya constellation was the best alternative when considering system performance, system cost, current MILSATCOM system compatibility and the technology required for system implementation.

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